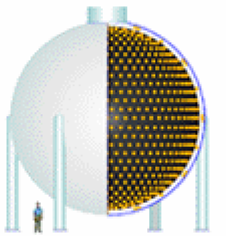


MiniBooNE and NuMI – Why do they need so many protons?

Eric Prebys

Fermilab Accelerator Division/MiniBooNE

Preface

- The turn-on of the LHC in ~2007 will mark the end of the Fermilab Tevatron's unprecedented 20+ year reign as the world's highest energy collider.
- With the cancellation of the BTeV (B physics) project, the collider program is scheduled to be terminated in 2009, possibly sooner.
- The lab has a strong commitment to the International Linear Collider, but physics results are at least 15 years away.
- -> Neutrino physics will be the centerpiece of Fermilab science for at least a decade.

Luckily, neutrinos are very interesting

- Multi-disciplinary
  - Study
    - Solar
    - Atmospheric
    - Reactor
    - Lab based (beta-decay)
    - Accelerator Based
  - Relevance
    - Particle physics
    - Astrophysics
    - Cosmology
- Many unanswered questions
  - Type: Dirac vs. Majorana
  - Generations: 3 active, but possibly sterile
  - Masses and mass differences
  - Mixing angles
  - CP and possibly even CPT violation
- Trying to coordinate the effort and priorities
  - See "APS Multidivisional Neutrino Study"
    - http://www.aps.org/neutrino/

The Growing Excitement of Neutrino Physics

Pauli Predicts the Neutrino

Fermi's theory of weak interactions

Reines & Cowan discover (anti)neutrinos

Davis discovers the solar deficit

2 distinct flavors identified

Kamioka II confirms solar deficit

LEP shows 3 active flavors

SAGE and Gallex see the solar deficit

Kamioka II and IMB see atmospheric neutrino anomaly

Kamioka II and IMB see supernova neutrinos

Nobel prize for discovery of distinct flavors!

LSND sees possible indication of oscillation signal

Nobel Prize for $\overline{\nu}$ discovery!

Super K sees evidence of atmospheric neutrino oscillations

Super K confirms solar deficit and "images" sun

SNO shows solar oscillation to active flavor

Nobel Prize for neutrino astroparticle physics!

KamLAND confirms solar oscillations

K2K confirms atmospheric oscillations

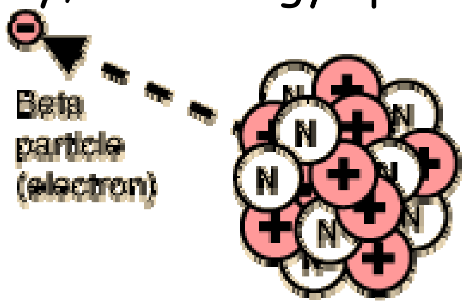
1930 1955 1980 2005

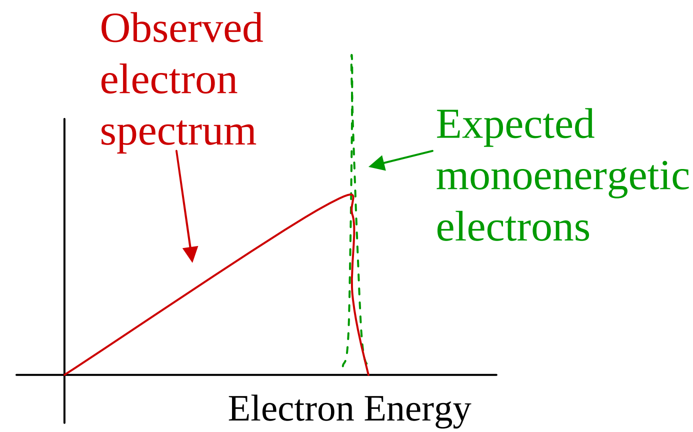
This Talk

- **A Brief History of Neutrinos**
  - Background
  - Neutrino “problem”
  - Neutrino oscillations
- **Some (recent) Key Experimental Results**
  - SuperKamiokande
  - SNO
  - Reactor Summary
  - K2K
  - LSND (????)
  - Where do we stand?
- **Major Fermilab Experiments**
  - MiniBooNE
  - NuMI/Minos
  - Nova
- **Meeting the Needs of these Experiments**
  - Existing Complex
  - Post-Collider
  - Longer Term

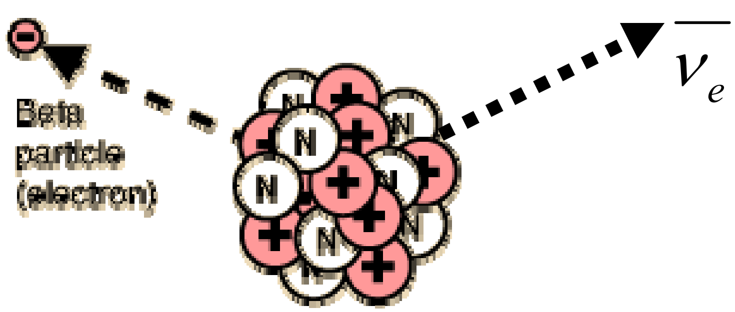
A Brief History of Neutrinos: The Beginning

In "beta decay", one element changes to another when the nucleus emits an electron (or positron). Looked like a 2-body decay, but energy spectrum wrong.





In 1930, Wolfgang Pauli suggested a *"desperate remedy"*, in which an "invisible" particle was carrying away the missing energy. He called this particle a "neutron".



Enrico Fermi changed the name to "neutrino" in 1933, and it became an integral part of his **extremely successful** weak decay theory.

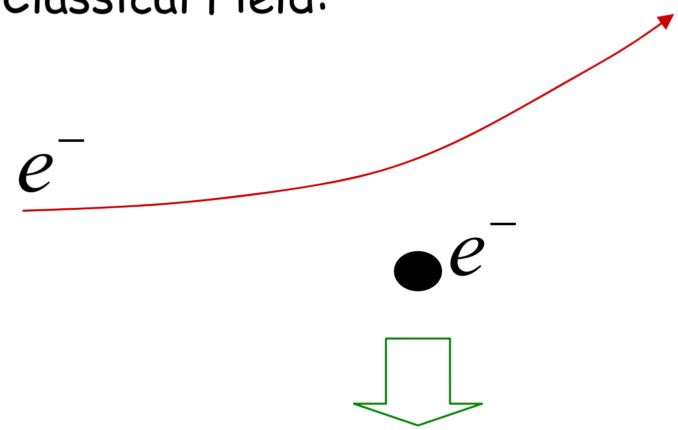
In 1956, Reines and Cowen observe first direct evidence of neutrinos – 26 years after their prediction!

The Question of Mass

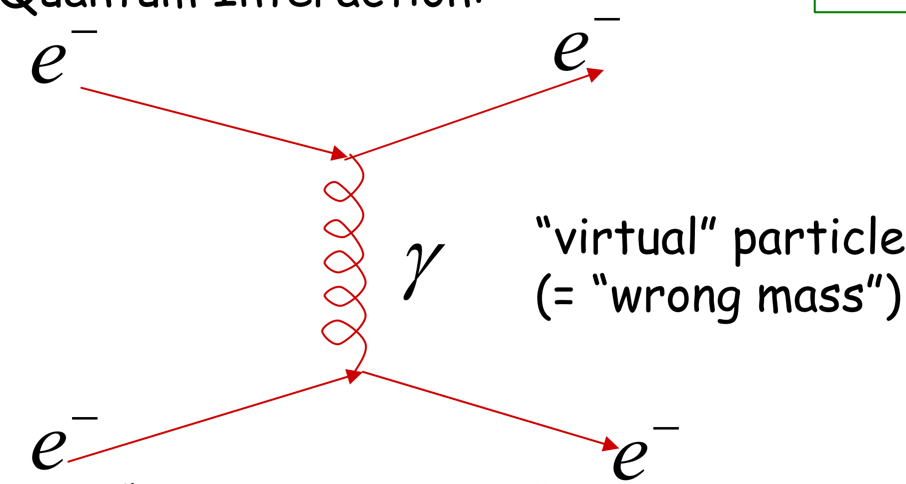
- All observed kinematics of neutrino interactions are consistent with *zero mass* to within the limits of sensitivity.
- In Fermi model, neutrinos are massless *by definition*
- 1962: Lederman, Steinberger, and Schwartz show that that there are at least two distinct "flavors" of neutrinos ($\nu_\mu \neq \nu_e$), both apparently *massless*.
- 1970's: "Standard Model" completed – with *massless* neutrinos (and only 18 parameters).

Particle Physics 101

Classical Field:

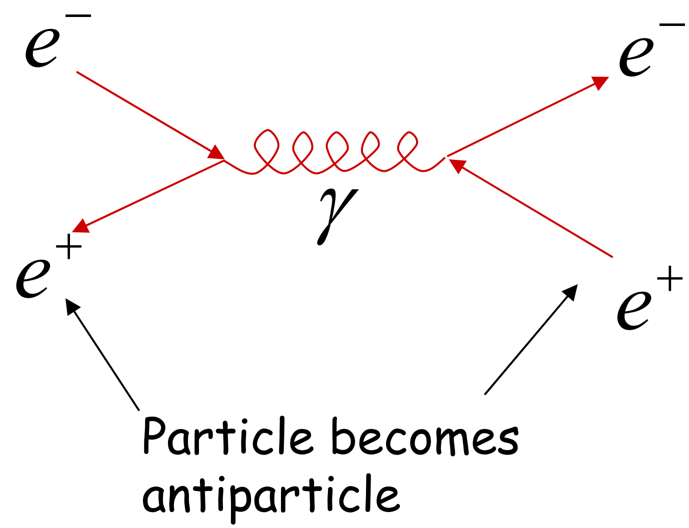


Quantum Interaction:



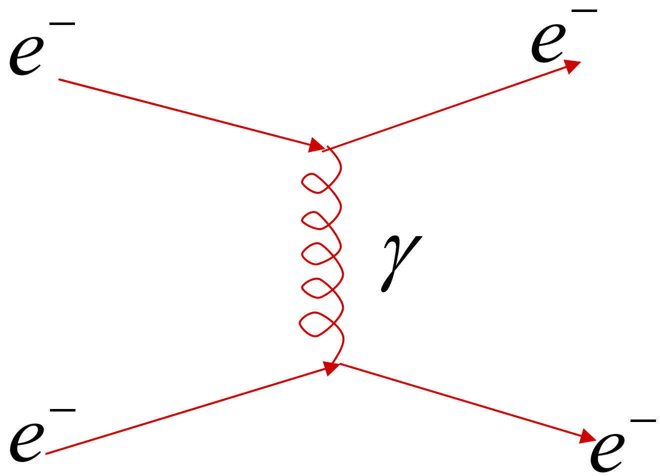
"Feynman Diagram"

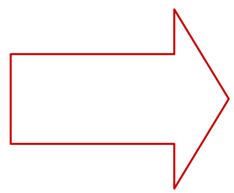
Can also change orientation of diagram:



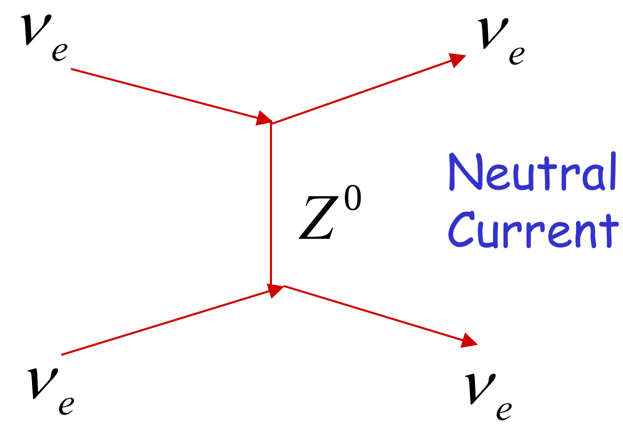
Weak Interactions

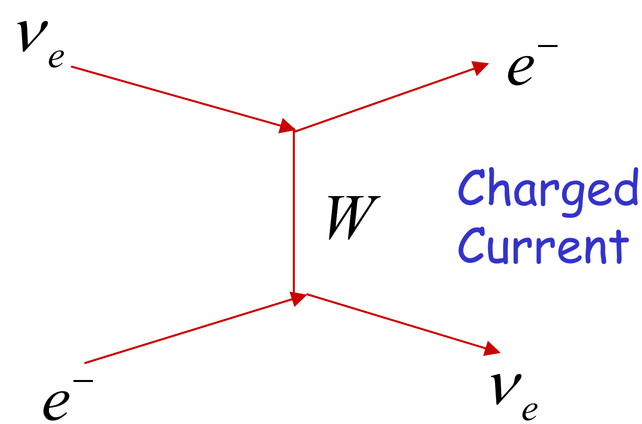
Quantum Electrodynamics (QED)





Electroweak Theory:



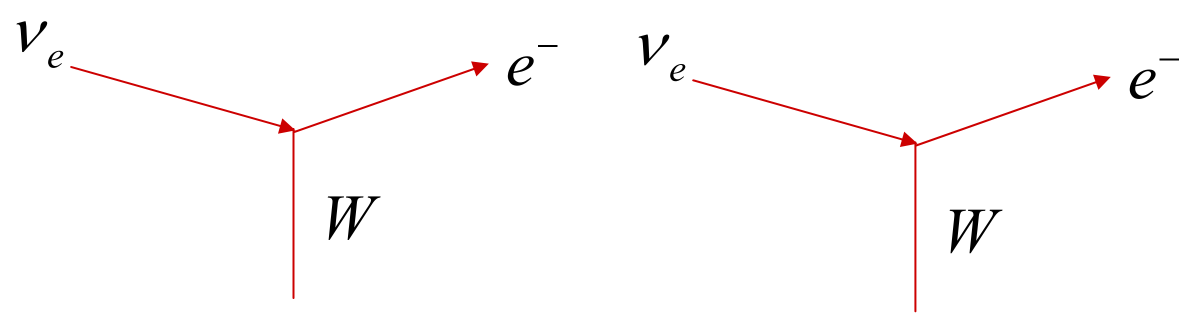


Neutrinos in the Standard Model

Each Generation lepton has an associated neutrino, just as each "up-type" quark has a "down-type" partner

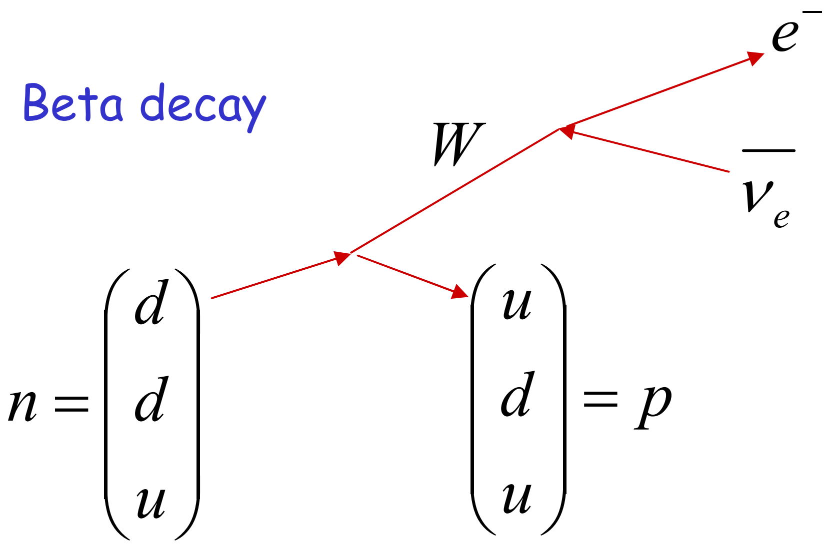
$$\begin{pmatrix} u \\ \updownarrow \\ d \end{pmatrix} \begin{pmatrix} c \\ \updownarrow \\ s \end{pmatrix} \begin{pmatrix} t \\ \updownarrow \\ b \end{pmatrix} \Rightarrow \begin{pmatrix} e^- \\ \updownarrow \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu^- \\ \updownarrow \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau^- \\ \updownarrow \\ \nu_\tau \end{pmatrix}$$

A charged weak interaction causes a "flip" between partners



Weak Decays

Beta decay

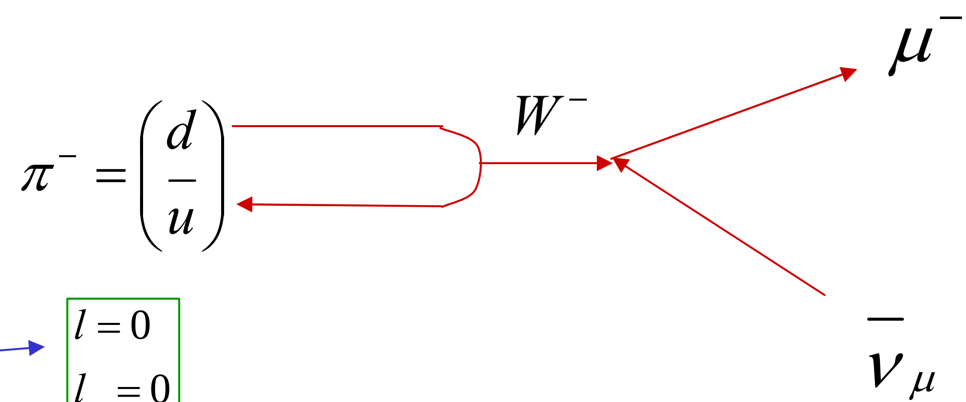


$$n \to p + e^- + \overline{\nu}_e$$

Pion decay

$$\pi^- \to \mu^- + \overline{\nu}_\mu$$

$l = 1$
$l_\mu = 1$



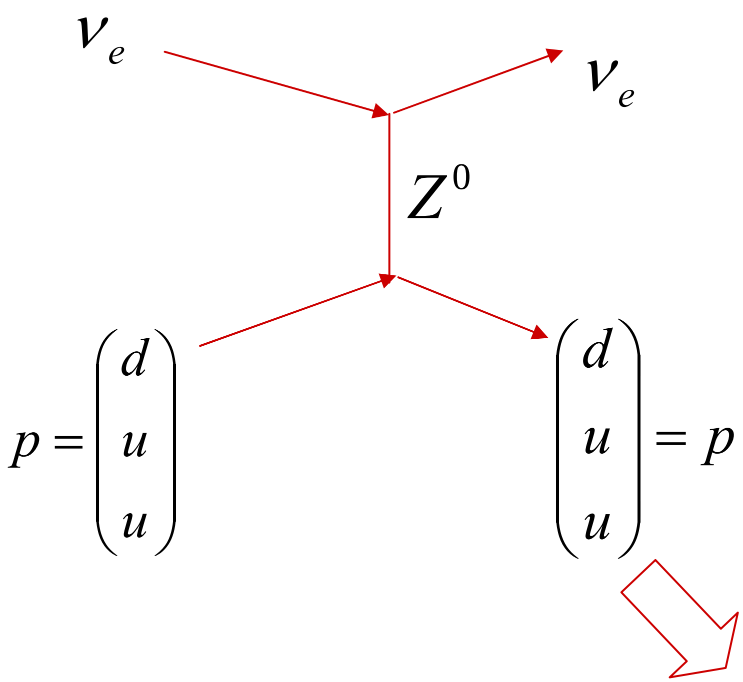
"Lepton number" conserved

$l = 0$
$l_\mu = 0$

$l = -1$
$l_\mu = -1$

Examples of Neutrino Interactions

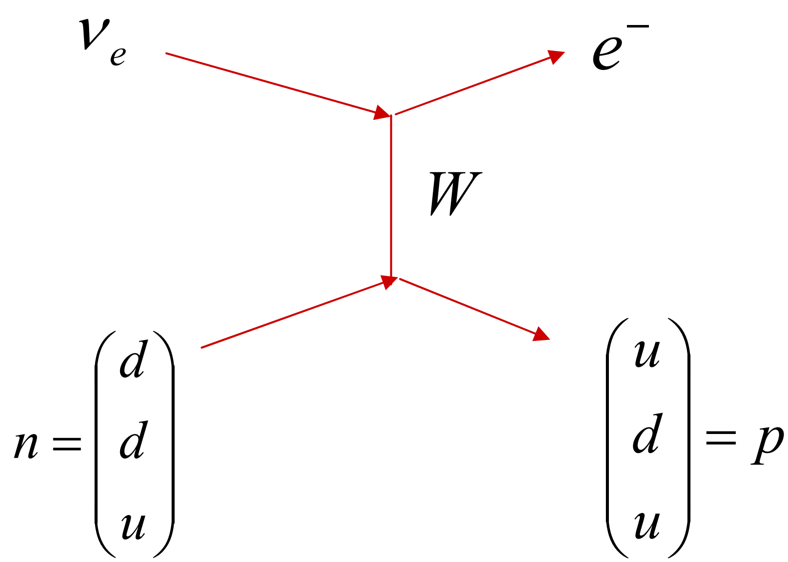
elastic scattering



Detect scattered
proton (or neucleus)

Quasi-elastic scattering

Detect charged particle
"out of nowhere"



The Neutrino "Problem"

- 1968: Experiment in the Homestake Mine first observes neutrinos from the Sun, **but there are far fewer than predicted**. Possibilities:
  - Experiment wrong?
  - Solar Model wrong? *(⇐ believed by most not involved)*
  - Enough created, but maybe oscillated (or decayed to something else) along the way.

Solar Problem

- ~1987: Also appeared to be too few atmospheric muon neutrinos. Less uncertainty in prediction. Similar explanation.

Atmospheric Problem

- Both results confirmed by numerous experiments over the years.
- 1998: SuperKamiokande observes clear oscillatory behavior in signals from atmospheric neutrinos. For most, this establishes neutrino oscillations "beyond a reasonable doubt" (more about this shortly)

Theory of Neutrino Oscillations

- Neutrinos are produced as *weak eigenstates* (ν_e, ν_μ, or ν_τ).
- In general, these can be represented as *linear combination of mass eigenstates*.
- If the above matrix is not diagonal *and* the masses are not equal, then the net weak flavor content will *oscillate* as the neutrinos propagate.
- **Example:** if there is mixing between the ν_e and ν_μ:

Flavor eigenstates →
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$
← Mass eigenstates

then the probability that a ν_e will be detected as a ν_μ after a distance L is:

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2\left(1.27 \bullet \Delta m^2 \bullet \frac{L}{E}\right)$$

Distance in *km*

Energy in GeV

$m_2^2 - m_1^2$ (in eV^2)

Only measure *magnitude* of the *difference* of the square of the masses!

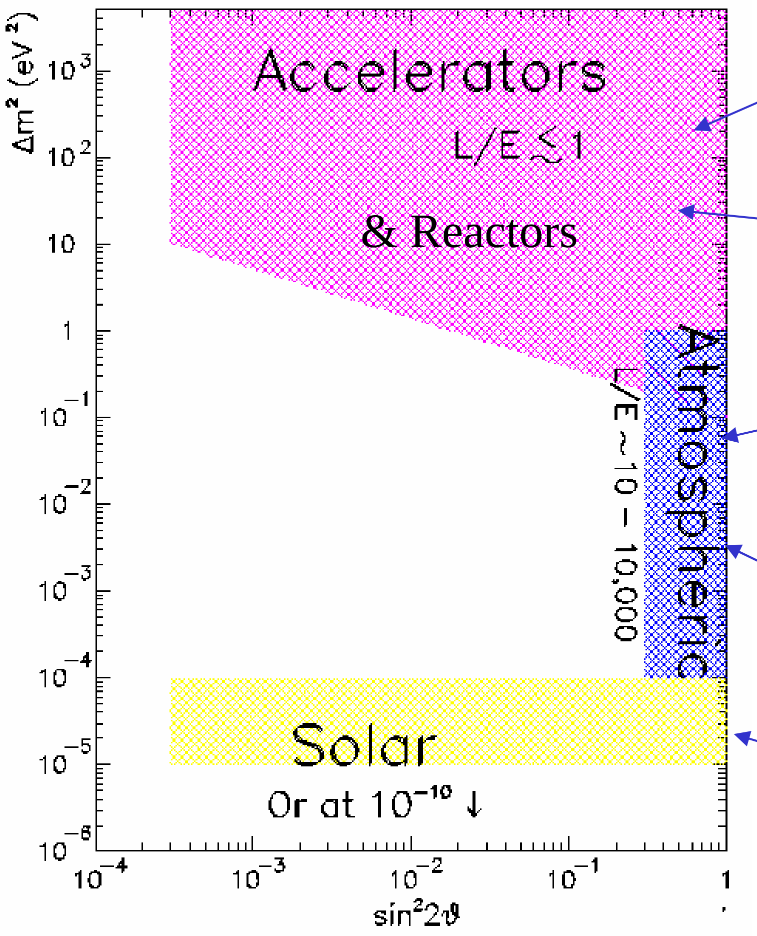
Problem: need a heck of a lot of neutrinos to study this!

Sources of a Heck of a Lot of Neutrinos

- The sun:
  - Mechanism: nuclear reactions
  - Pros: free
  - Cons: only electron neutrinos, low energy, exact flux hard to calculate, can't turn it on and off.
- Atmosphere:
  - Mechanism: Cosmic rays make pions, which decay to muons, electrons, and neutrinos.
  - Pros: free, muon and electron neutrinos, higher energy than solar neutrinos, flux easier to calculate.
  - Cons: flux fairly low, can't turn it on and off.
- Nuclear Reactors:
  - Mechanism: nuclear reactions.
  - Pros: "free", they do go on and off.
  - Cons: only electron neutrinos, low energy, little control of on and off cycles.
- Accelerators:
  - Mechanism: beam dumps -> particle decays + shielding -> neutrinos
  - Pros: Can get all flavors of neutrinos, higher energy, can control source.
  - Cons: NOT free

Probing Neutrino Mass Differences

Different experiments probe different ranges of $\frac{L}{E}$ ← Path length, ← Energy



Accelerators use π decay to *directly* probe $\nu_\mu \rightarrow \nu_e$

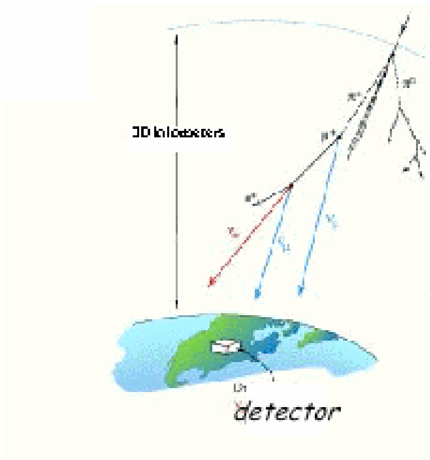
Reactors use use *disappearance* to probe $\nu_e \rightarrow$?

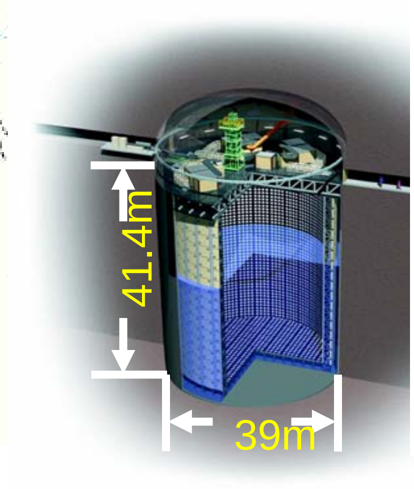
Cerenkov detectors directly measure ν_μ and ν_e content in atmospheric neutrinos. Fit to $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$ mixing hypotheses

Also probe with "long baseline" accelerator experiments

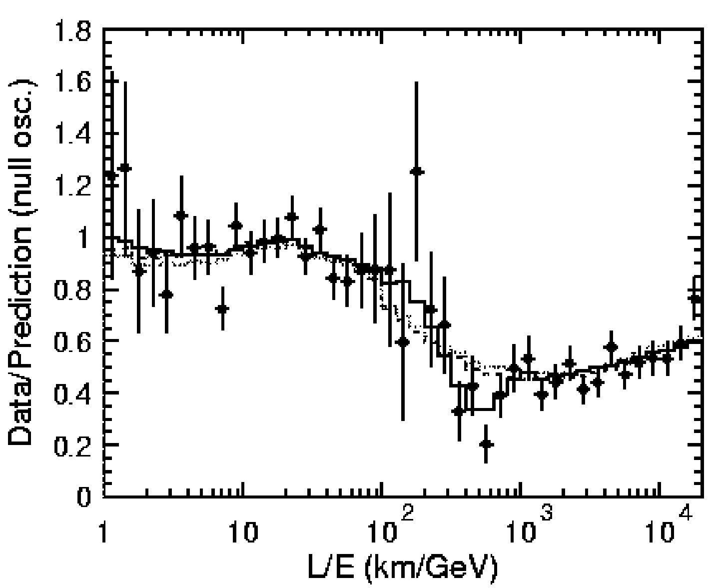
Solar neutrino experiments typically measure the disappearance of ν_e.

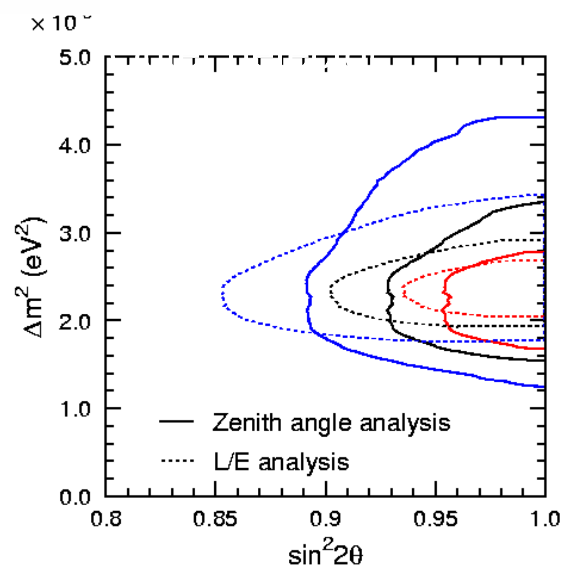
SuperKamiokande Atmospheric Result





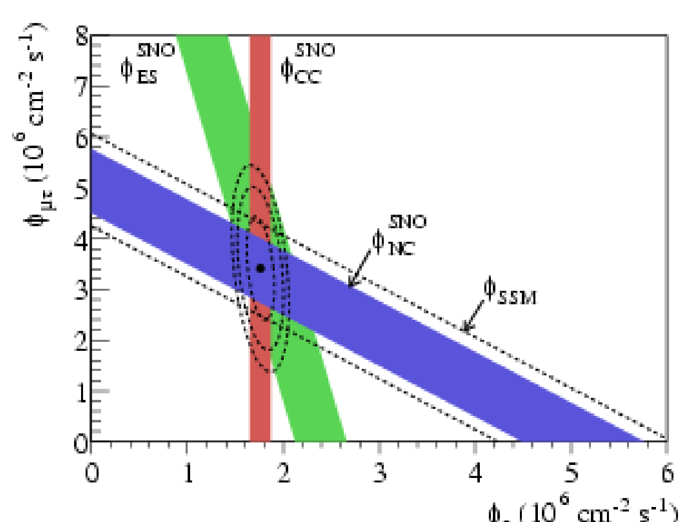
- Huge water Cerenkov detector can directly measure ν_μ and ν_e signals.
- Use azimuthal dependence to measure distance traveled (through the Earth)
- Positive result announced in 1998.
- Consistent with $\nu_\mu \leftrightarrow \nu_\tau$ mixing.

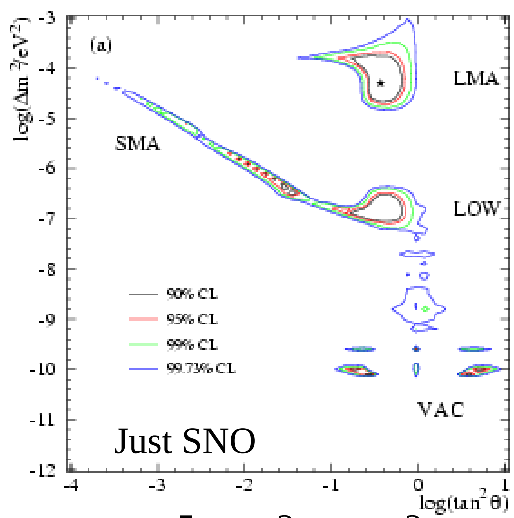


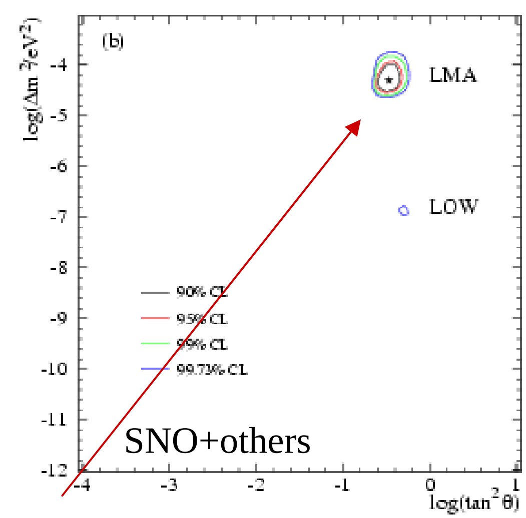


SNO Solar Neutrino Result

- Looked for Cerenkov signals in a large detector filled with heavy water.
- Focus on ^8B neutrinos
- Used 3 reactions:
  - $\nu_e + d \rightarrow p + p + e^-$: only sensitive to ν_e
  - $\nu_x + d \rightarrow p + n + \nu_x$: equally sensitive to ν_e, ν_μ, ν_τ
  - $\nu_x + e^- \rightarrow \nu_x + e^-$: 6 times more sensitive to ν_e than ν_μ, ν_τ d
- Consistent with initial full SSM flux of ν_e's mixing to ν_μ, ν_τ



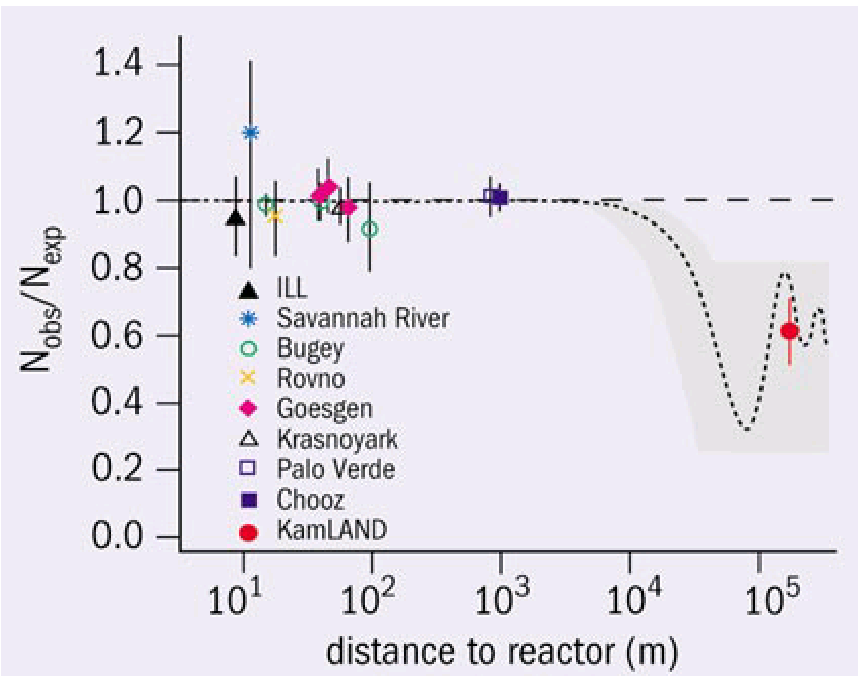


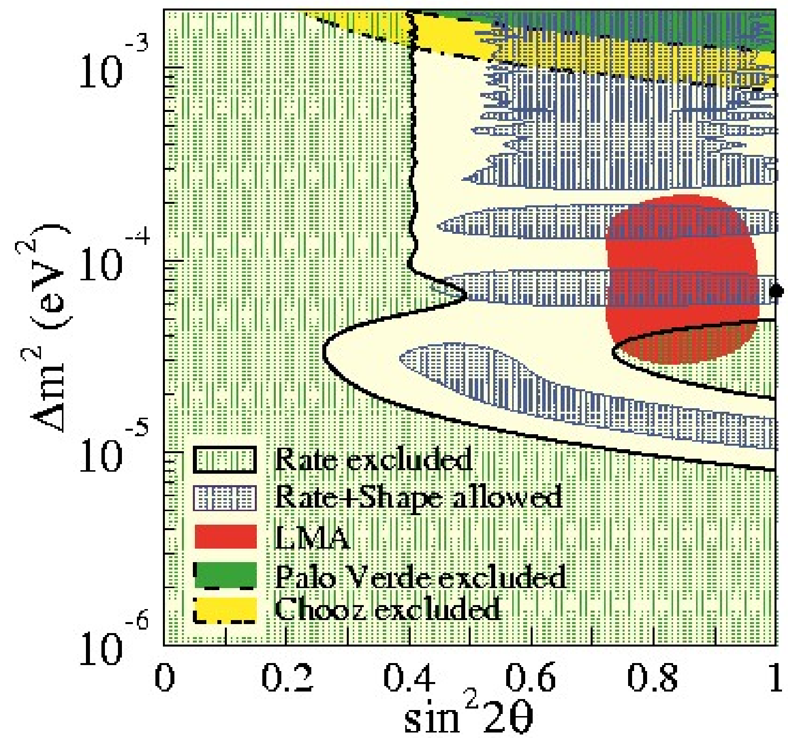


$$\text{Favor}: \Delta m^2 \approx 5\times10^{-5}\,\text{eV}^2; \tan^2\theta \approx .34$$

Reactor Experimental Results

- Single reactor experiments (Chooz, Bugey, etc). Look for ν_e disappearance: all negative
- KamLAND (single scintillator detector looking at ALL Japanese reactors): ν_e disappearance consistent with mixing.

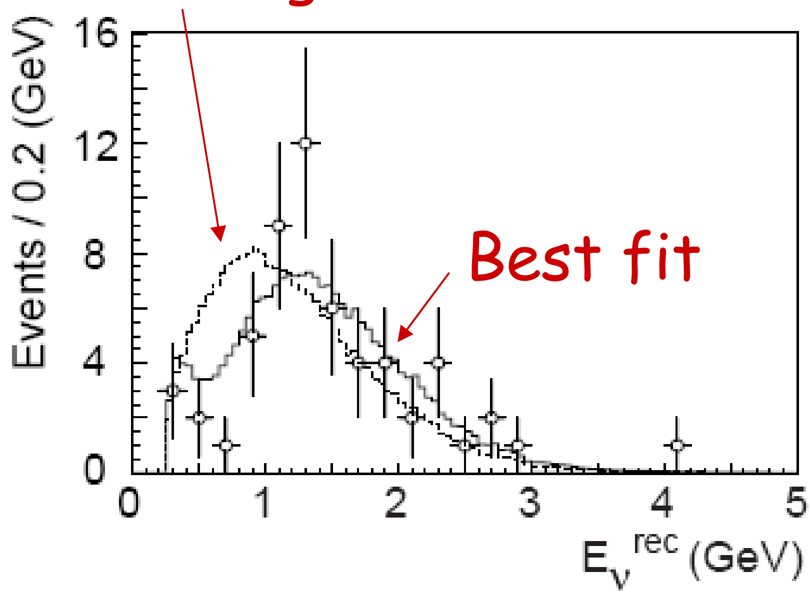




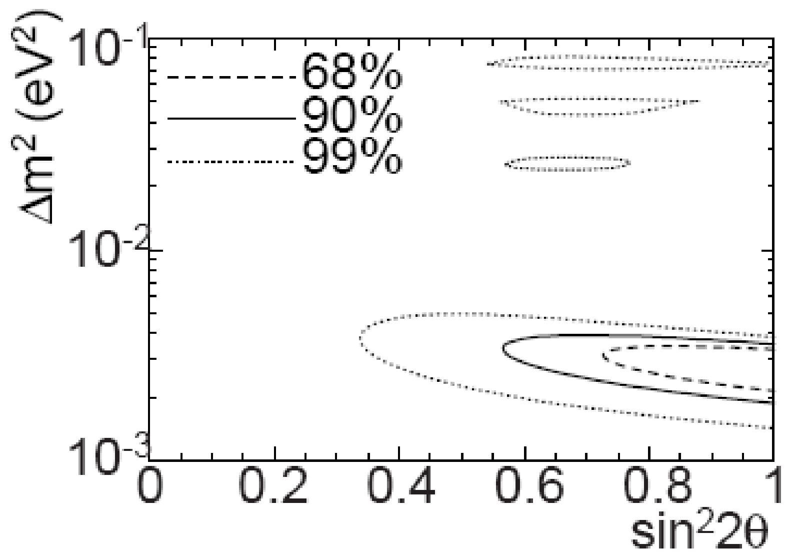
K2K

- First "long baseline Experiment
  - Beam from KEK PS to Kamiokande, 250 km away
  - Look for ν_μ disappearance (atmospheric "problem")
  - Results consistent with mixing

No mixing

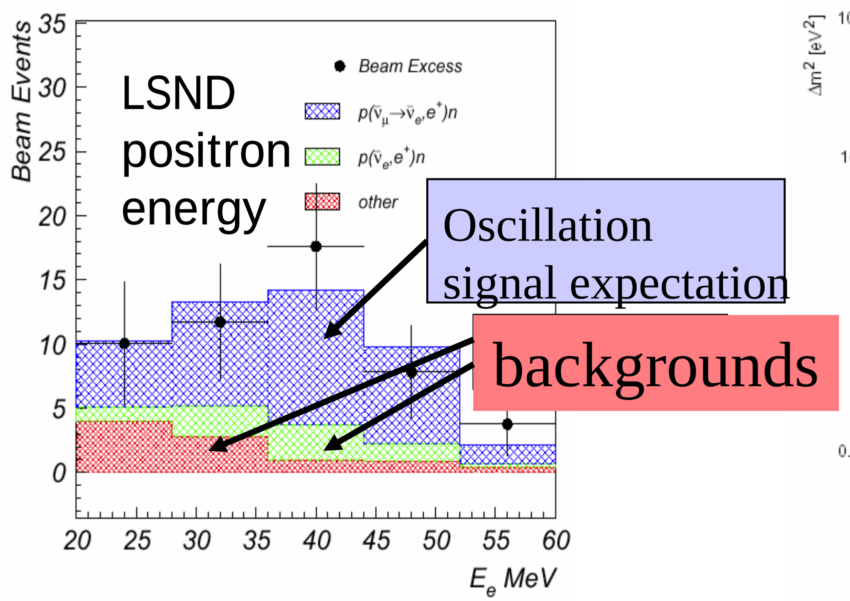


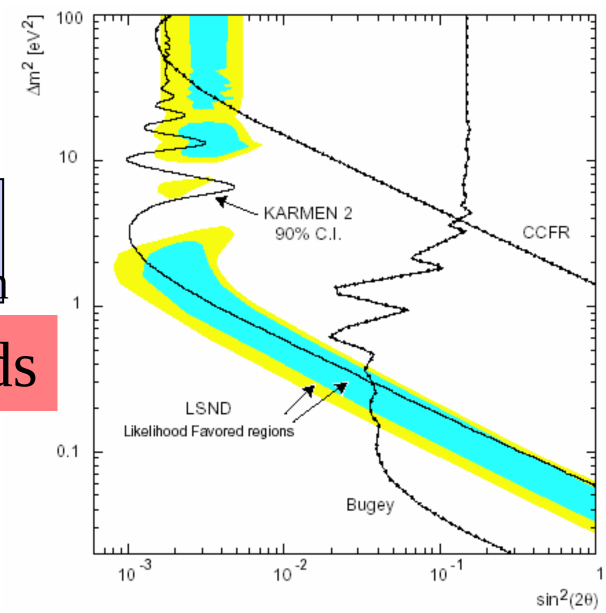
Allowed Mixing Region



LSND Experiment (odd man out)

- Looked for $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ in π decay from the 800 MeV LANSCE proton beam at Los Alamos
  - Look for $\bar{\nu}_e$ appearance via: $\bar{\nu}_e + p \to e^+ + n$
  - Look for ν_e appearance via: $\nu_e + C \to e^- + X$
- Observe excess in both channels (higher significance in $\bar{\nu}_e$)
- Only exclusive *appearance* result to date.
- Doesn't fit "nicely" with the other results!





$$\Delta m^2 \approx .05 - 1\,\mathrm{eV}^2$$

Full Mixing Picture (without LSND)

- General Mixing Parameterization

CP violating phase

$$\begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12}-s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12}-s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12}-s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12}-s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

QUARKS

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

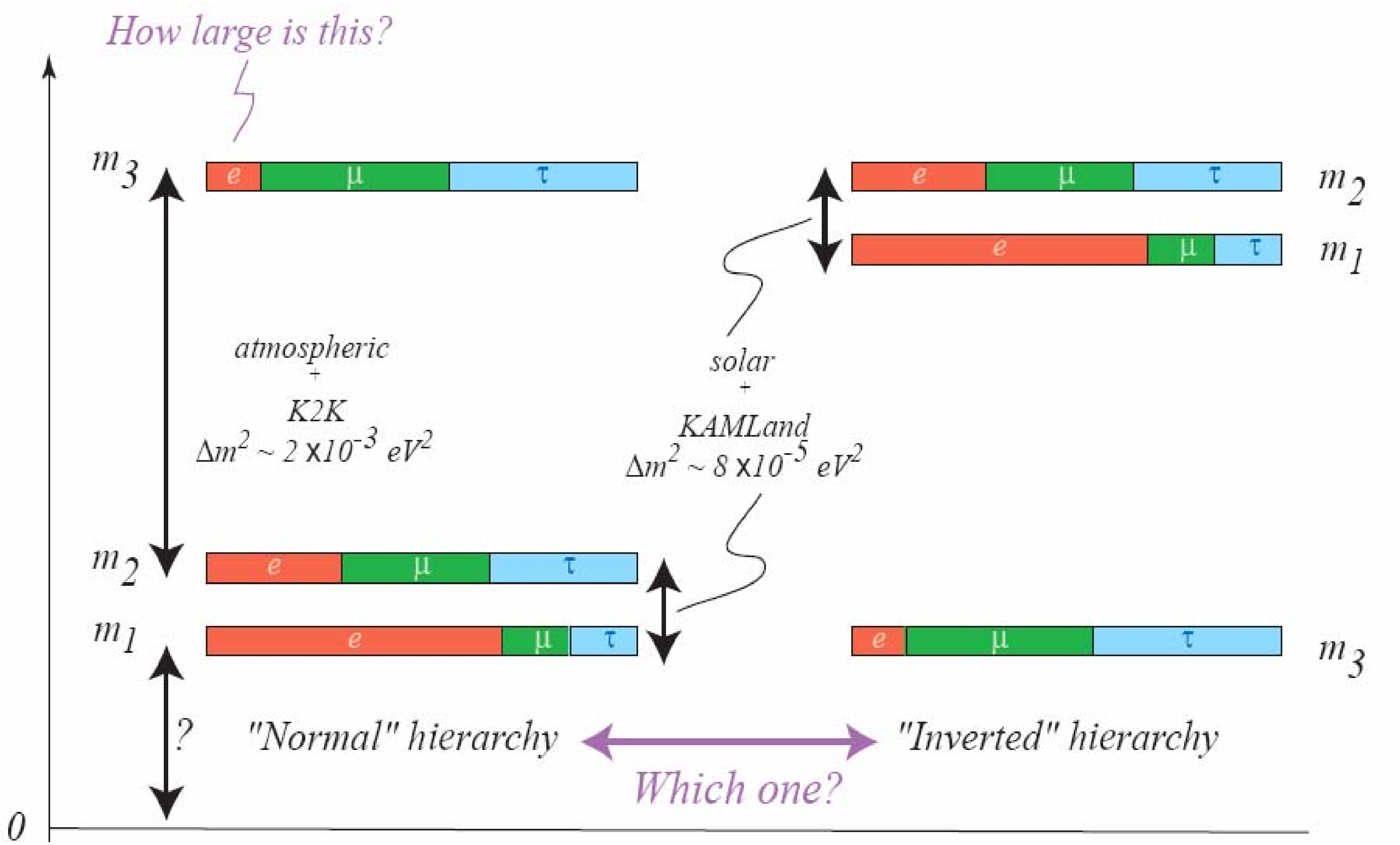
- Almost diagonal
- Third generation weakly coupled to first two
- "Wolfenstein Parameterization"

NEUTRINOS

$$U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

- Mixing large
- No easy simplification
- Think of mass and weak eigenstates as totally separate

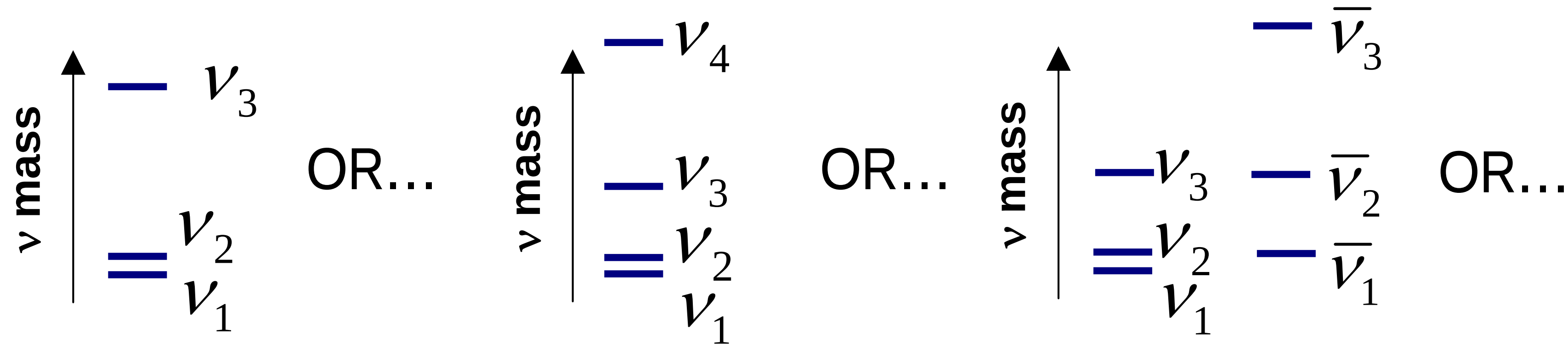
Neutrino Mixing (cont'd)



Incorporating LSND

We have 3 very different Δm^2's. Very hard to fit with only three mass states…

Only 3 active ν: | **3 active+1 sterile ν:** | **CPT violation:**



Only 3 active ν:

$$\text{solar}: \nu_e \to \nu_\mu$$
$$\text{atmos}: \nu_\mu \to \nu_e, \nu_\tau$$
$$\text{LSND}: \bar{\nu}_\mu \to \bar{\nu}_\tau \to \bar{\nu}_e$$

- not a good fit to data

3 active+1 sterile ν:

$$\text{solar}: \nu_e \to \nu_\mu, \nu_\tau$$
$$\text{atmos}: \nu_\mu \to \nu_\tau$$
$$\text{LSND}: \bar{\nu}_\mu \to \bar{\nu}_s \to \bar{\nu}_e$$

- possible(?)

CPT violation:

$$\text{solar}: \nu_e \to \nu_\mu$$
$$\text{atmos}: \nu_\mu \to \nu_\tau$$
$$\text{LSND}: \bar{\nu}_\mu \to \bar{\nu}_e$$

- possible(?)

Can fit three mass states quite well *without* LSND, but no a priori reason to throw it out. Must check…

Big Questions in Neutrino Physics

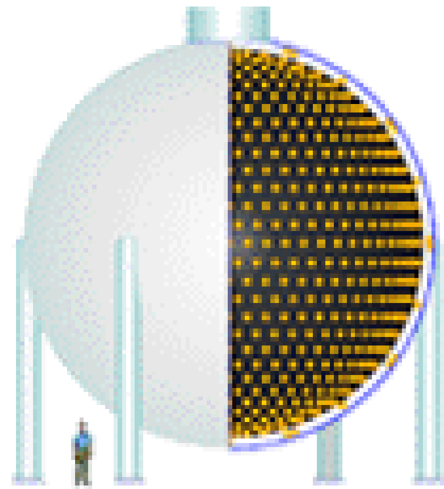
- Size of the mixing angles*
  - Particularly θ13
- Mass heirarchy*
  - Normal or Inverted
- Absolute masses
- Is neutrino Dirac or Majorana
  - i.e. is the neutrino its own antiparticle
- Is the LSND result correct?*
- CP violation parameters**

*Addressed by currently planned FNAL physics program

**Possibly addressed by future program

Enter the Fermilab Neutrino Program

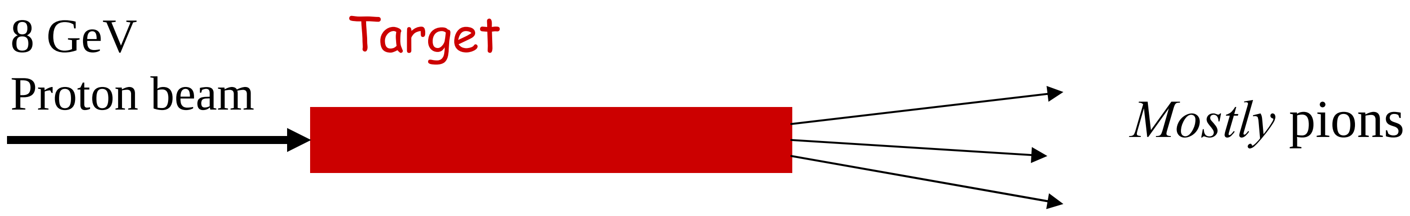
MiniBooNE-neutrinos from 8 GeV Booster proton beam (L/E~1): absolutely confirm or refute the LSND result

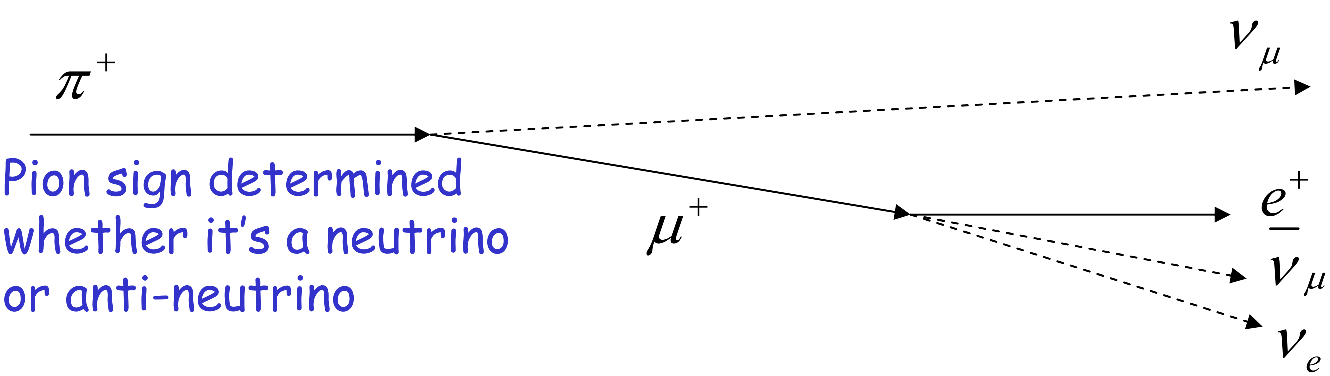


NuMI/Minos – neutrinos from 120 GeV Main Injector proton beam (L/E~100):

precision measurement of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations as seen in atmospheric neutrinos.

Producing Neutrinos At an Accelerator





Pion sign determined whether it's a neutrino or anti-neutrino

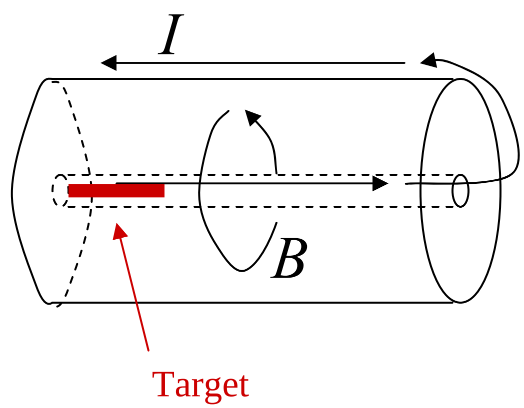
We will look for these to oscillate

Mostly lower energy

- Beam needs:
  - Lots of beam!!!
  - Short spills
    - to distinguish from cosmic background
  - Bucket structure
    - Use TOF to distinguish subrelativistic particles (mostly kaons)

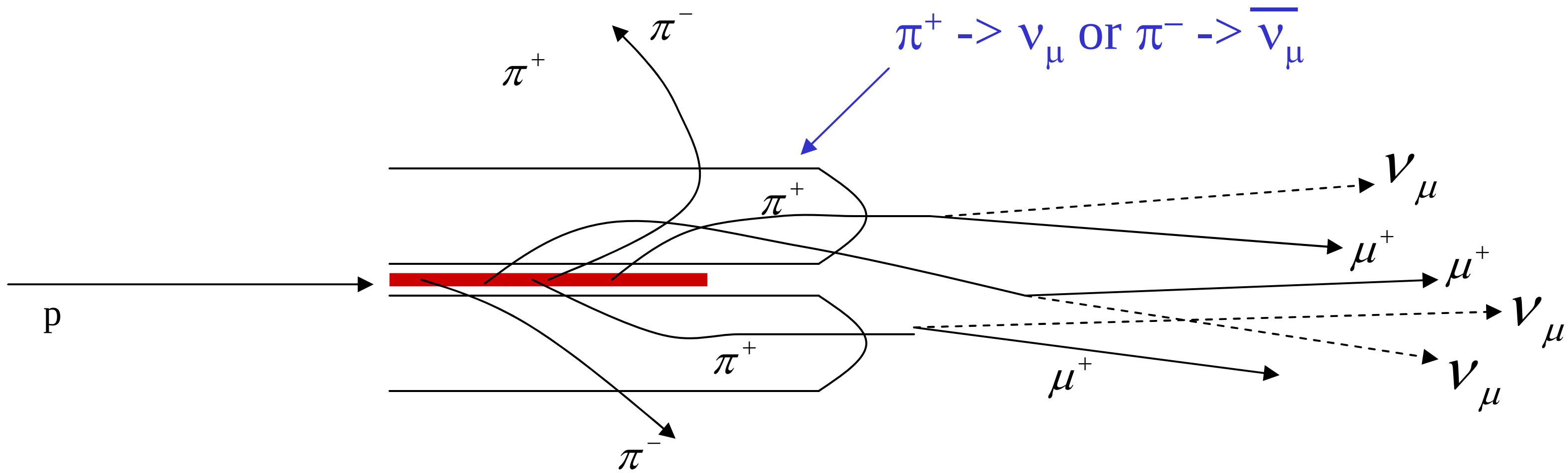
Neutrino Horn – "Focusing" Neutrinos

Can't focus neutrinos themselves, but they will go more or less where the parent particles go.

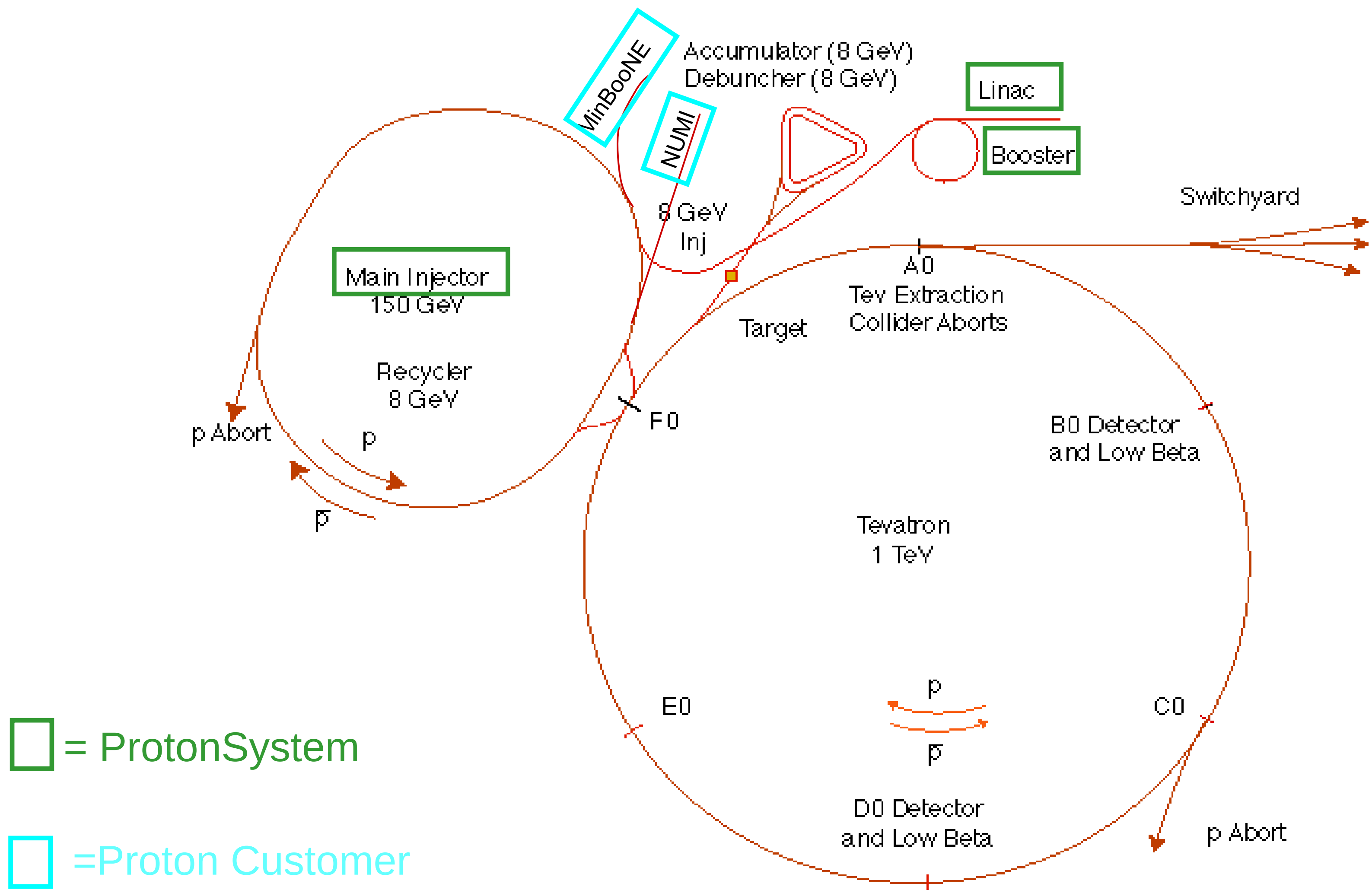


Coaxial "horn" will focus particles of a particular sign in both planes

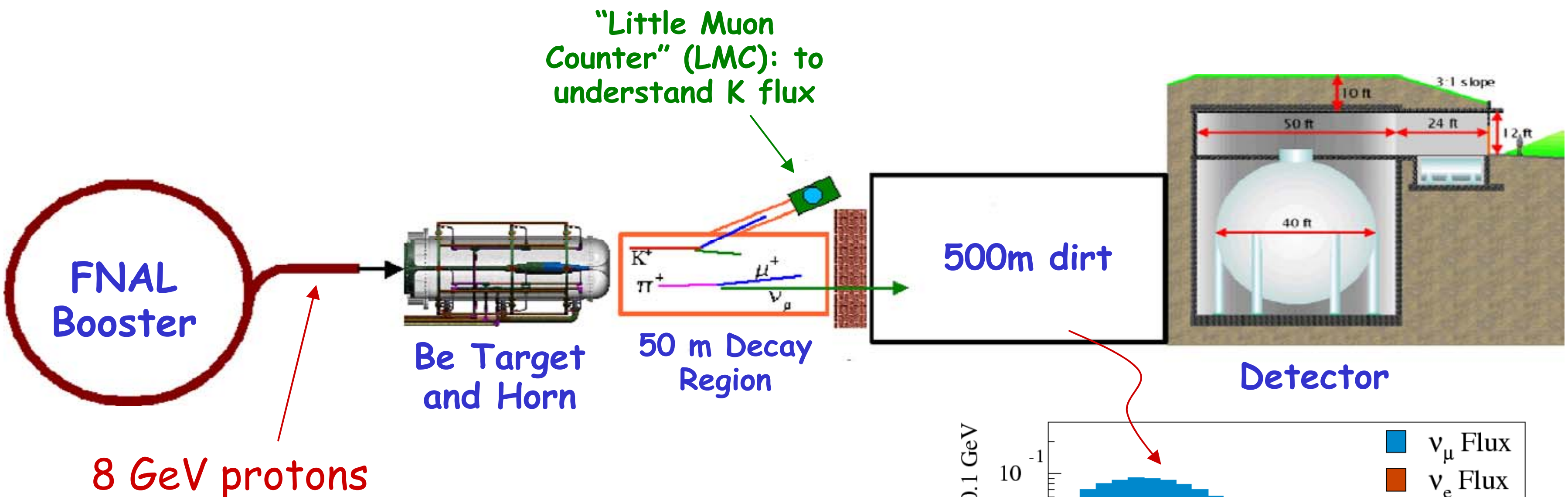
Horn current selects $\pi^+ \to \nu_\mu$ or $\pi^- \to \overline{\nu}_\mu$



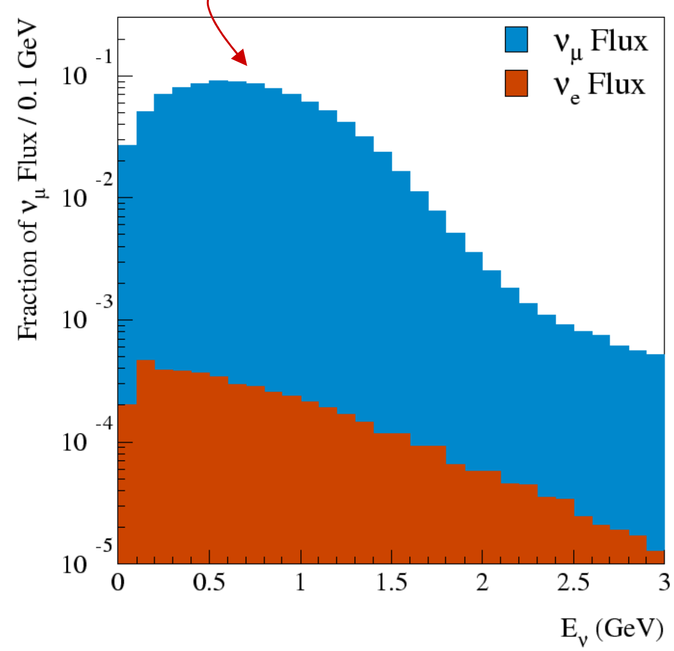
The Fermilab Accelerator Complex



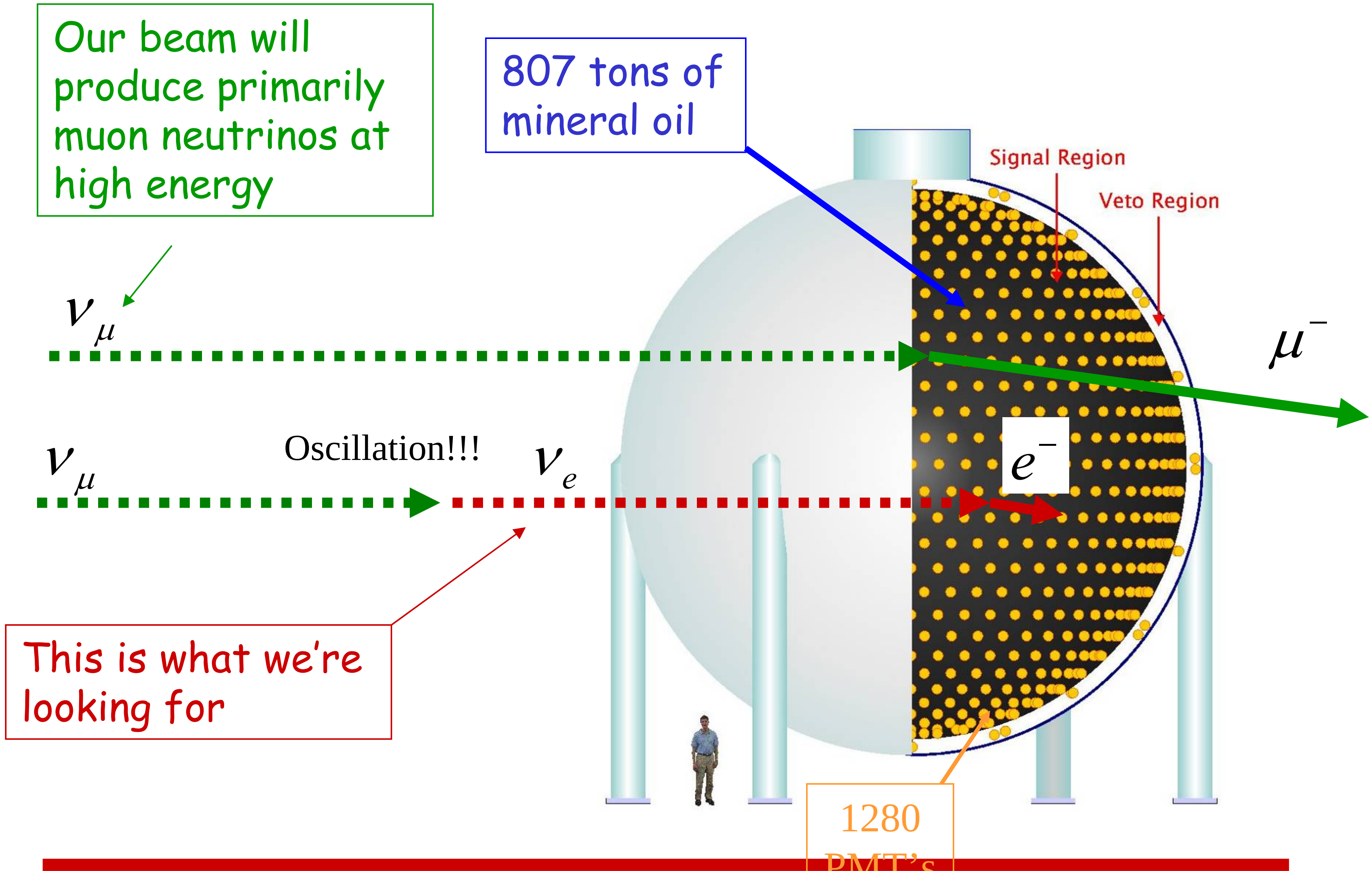
MiniBooNE Experiment



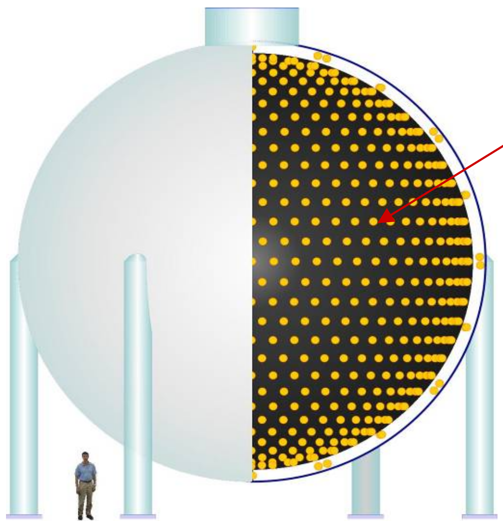
- Proton flux ~ 6E16 p/hr (goal 9E16 p/hr)
  - ~ 1 detected neutrino/minute
  - L/E ~ 1



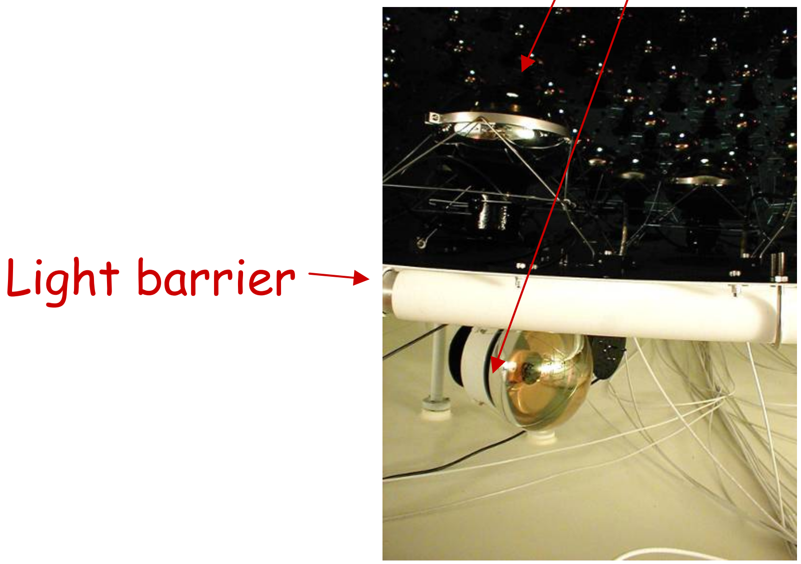
The MiniBooNE Detector



Detector

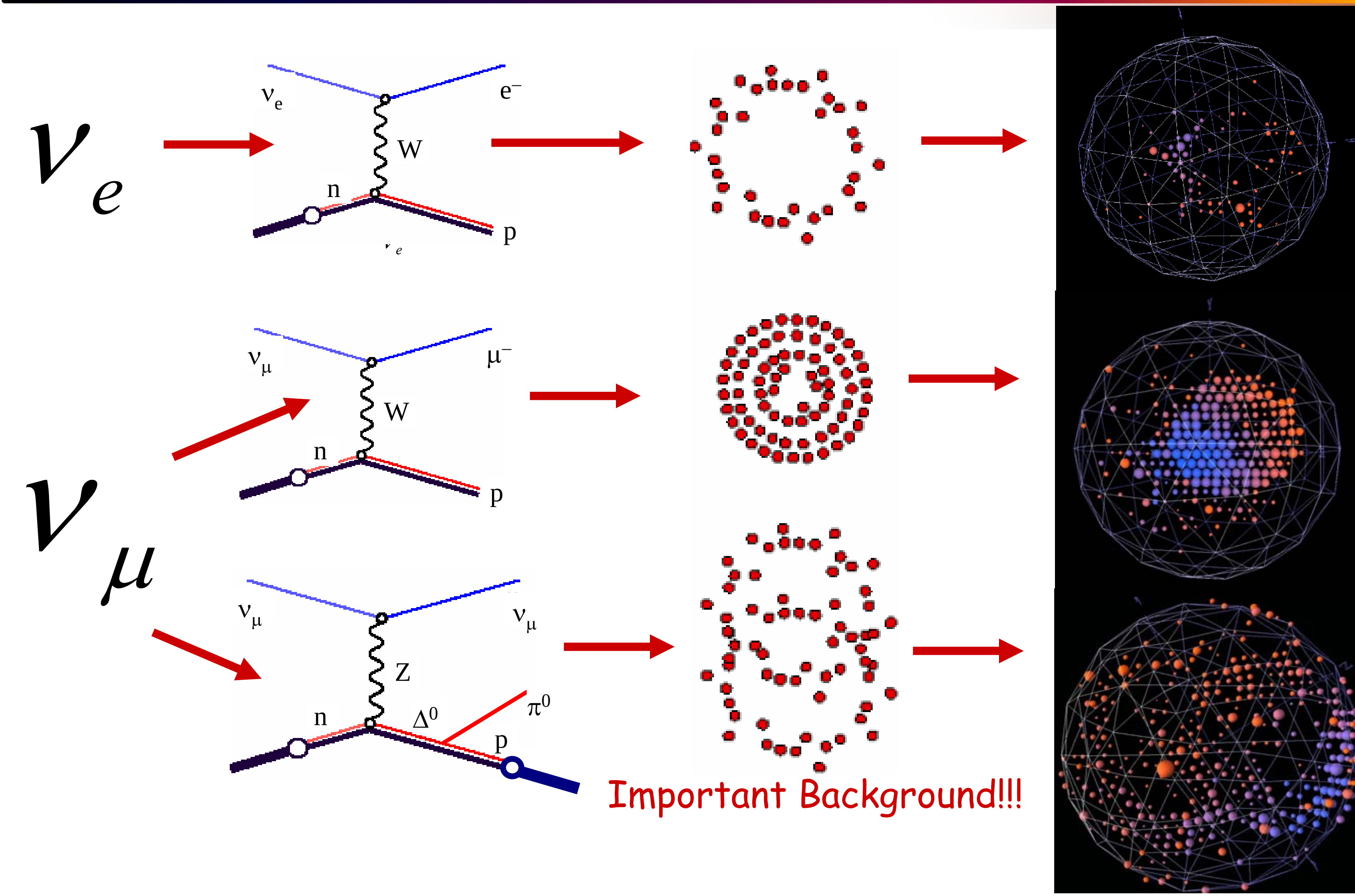


- 950,000 ℓ of pure mineral oil
- 1280 PMT's in inner region
- 240 PMT's outer veto region
- Light produced by Cerenkov radiation and scintillation

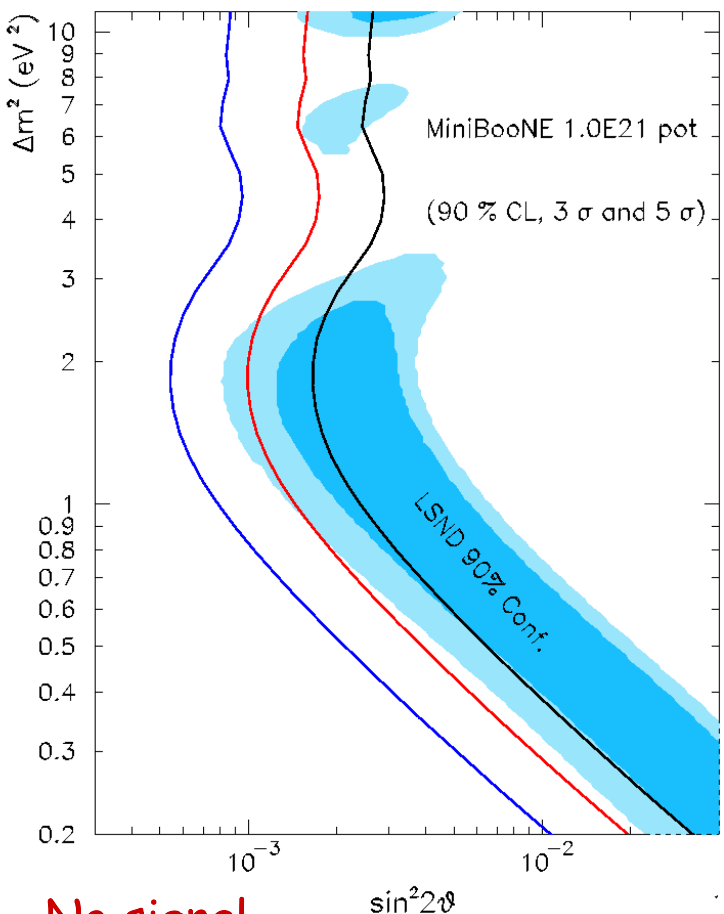


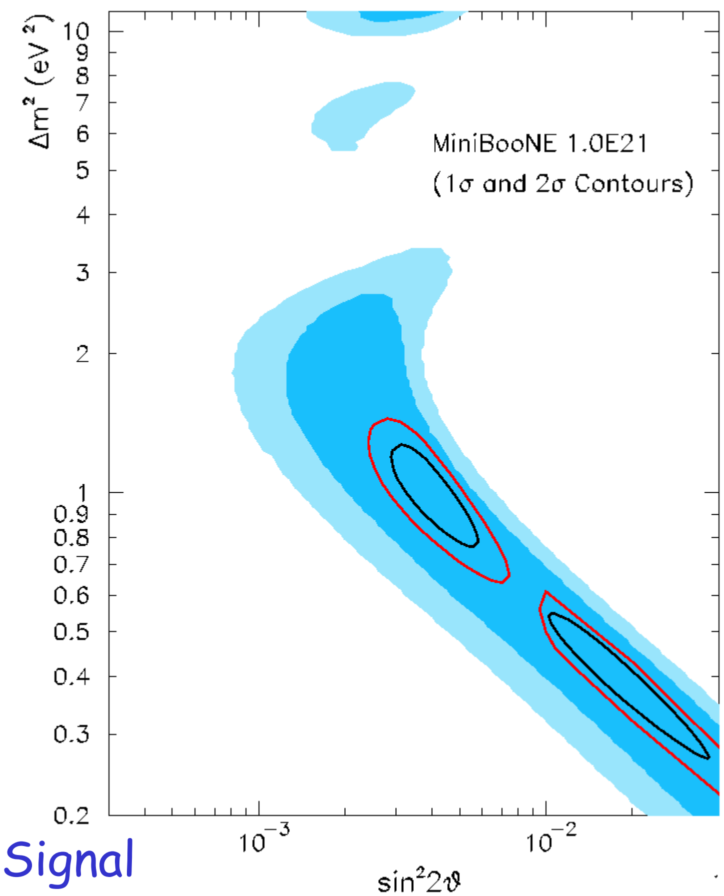
- Trigger:
  - All beam spills
  - Cosmic ray triggers
  - Laser/pulser triggers
  - Supernova trigger

Neutrino Detection/Particle ID



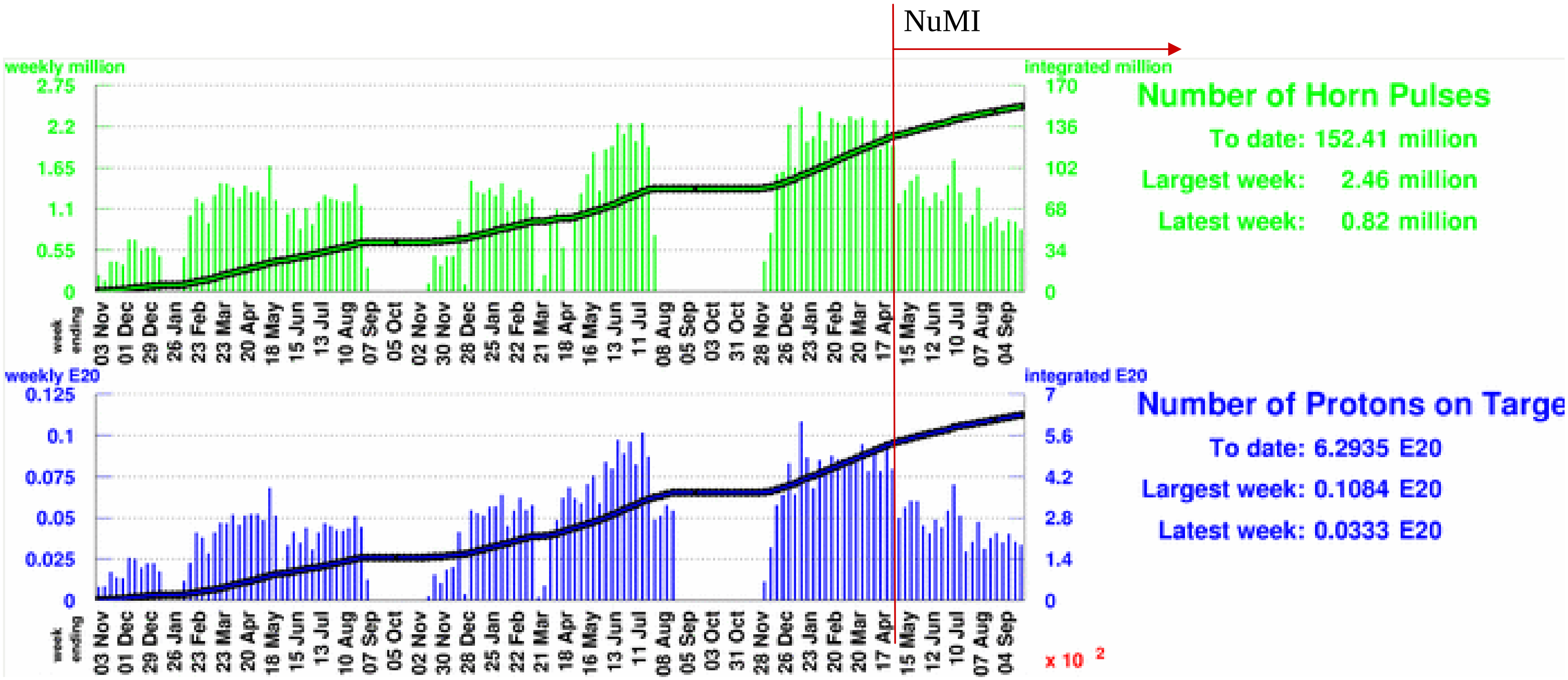
Experimental Sensitivity (1E21 POT)





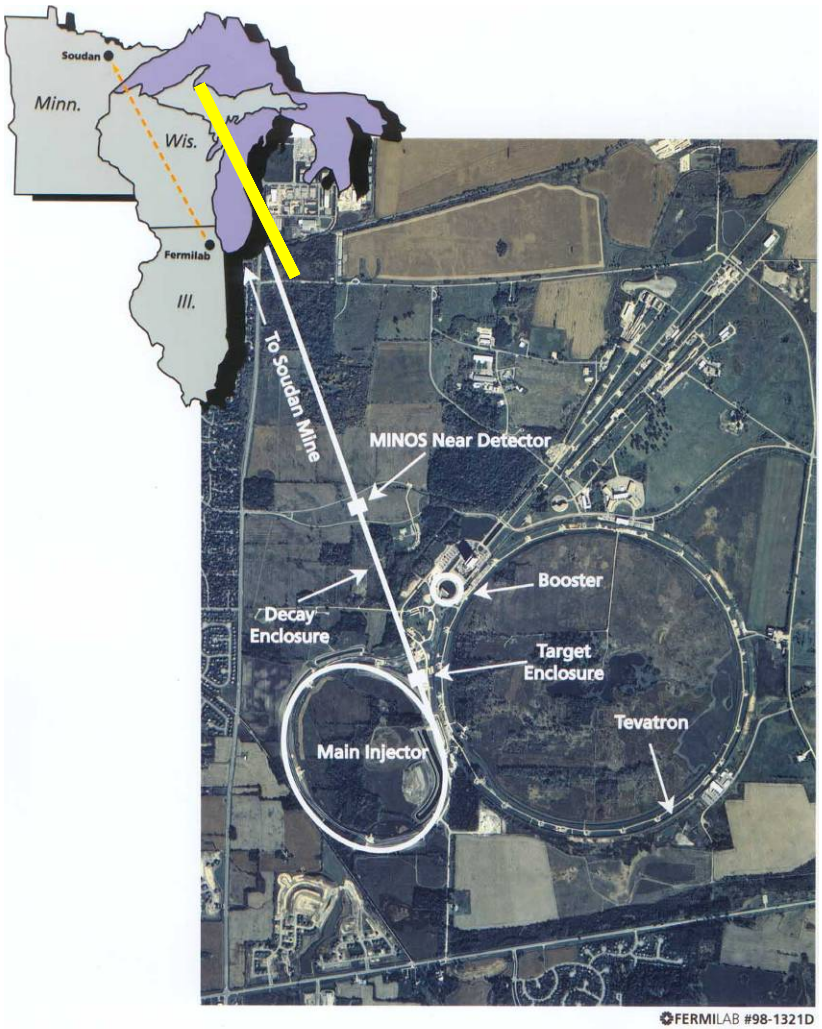
- No signal
  - Can exclude most of LSND at 5σ
- Signal
  - Can achieve good Δm^2 separation

Beam to MiniBooNE



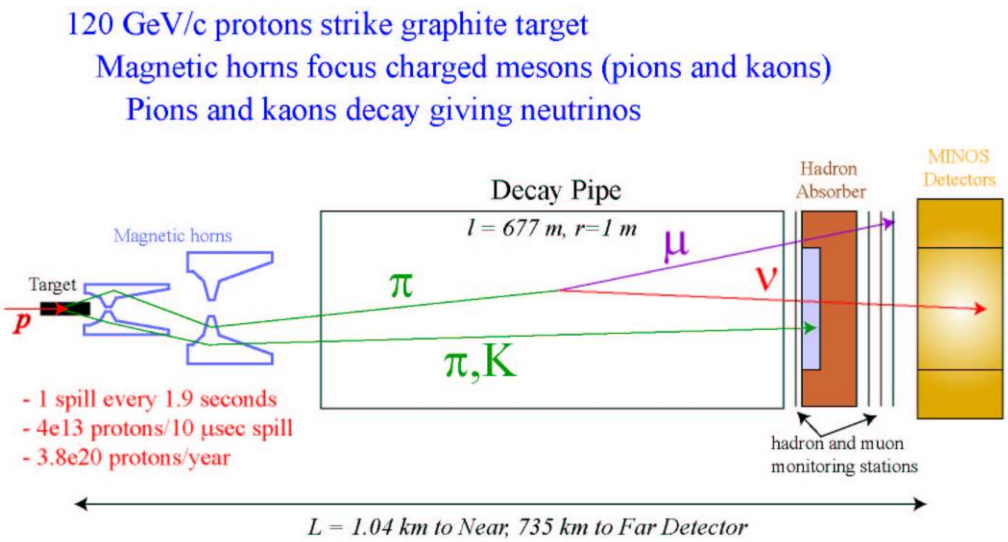
- 6.3E20 to date
- Plan for ~2E20/year during NuMI running
- First results in 2006

MINOS: Main Injector Neutrino Oscillation Study

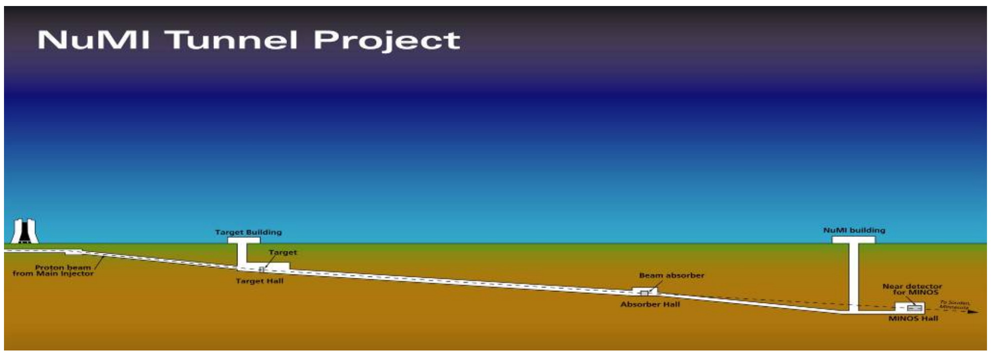


- 8 GeV Booster beam is injected into Main Injector.
- Accelerated to 120 GeV
- Transported to target
- Two detectors for understanding systematic
  - Near detector: FNAL (L=1km)
  - Far detector: Soudan Mine in Minnesota (735 km away)

NuMI beams



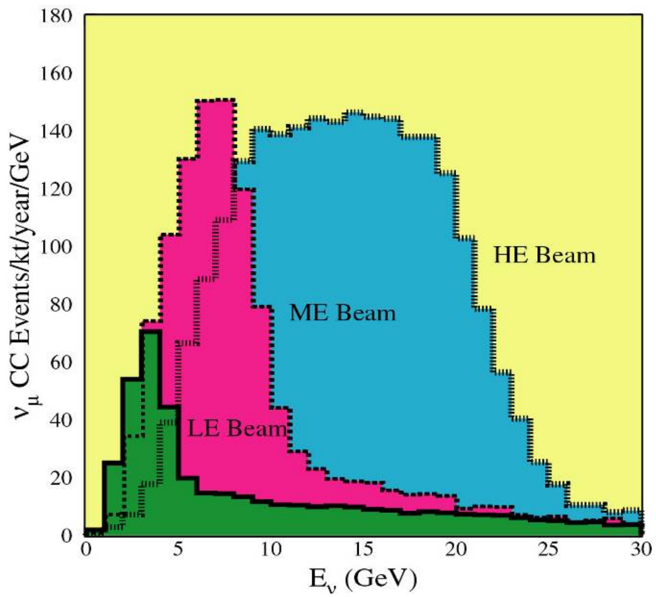
Two horns (second moveable) -> adjustable beam energy



Target

677 m decay pipe

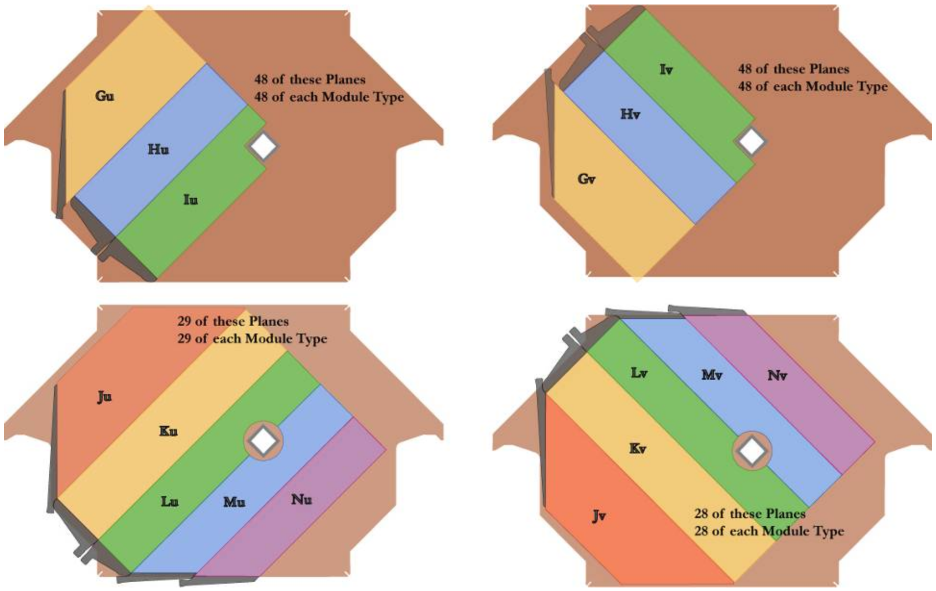
Near Detector



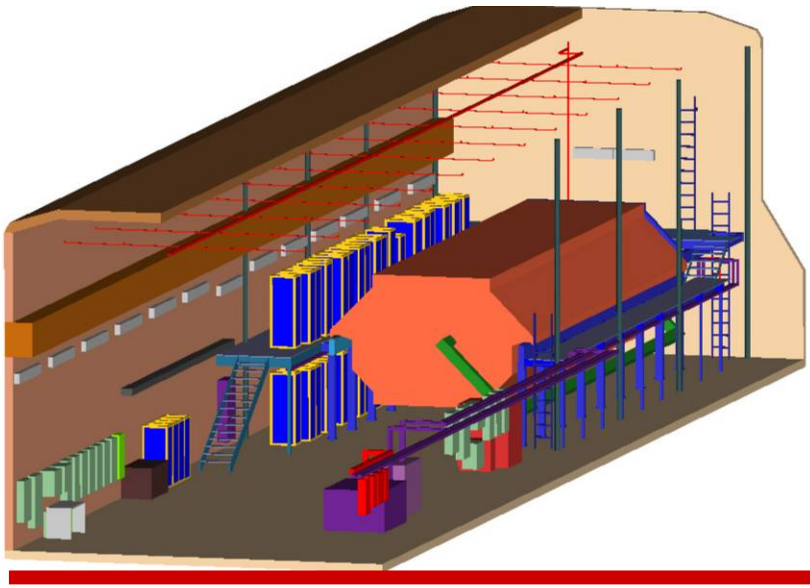
Near – 1040 m away

- 1 kton of steel plates
- Detect neutrinos through “appearance of charged particles
- Magnetic field in plates determines sign
- Range of particles separates particle types.

ν target region



μ spectrometer region

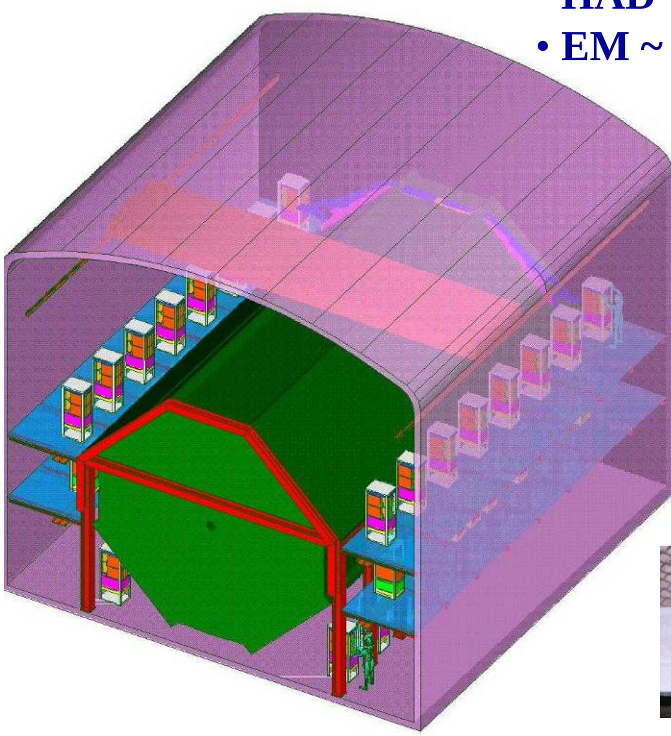


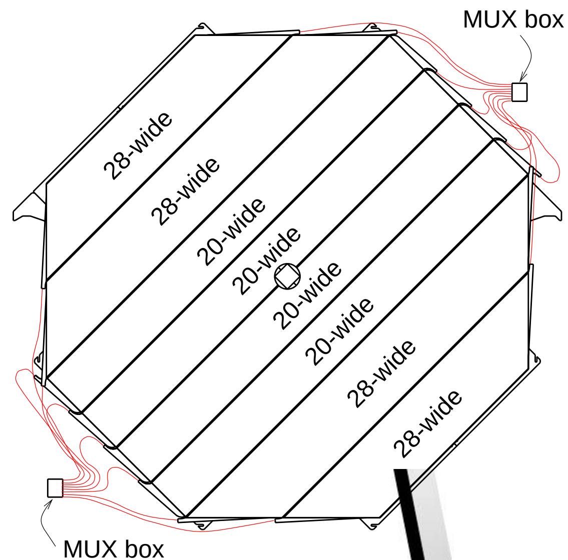
Near detector will provide high event statistics for “mundane” neutrino physics

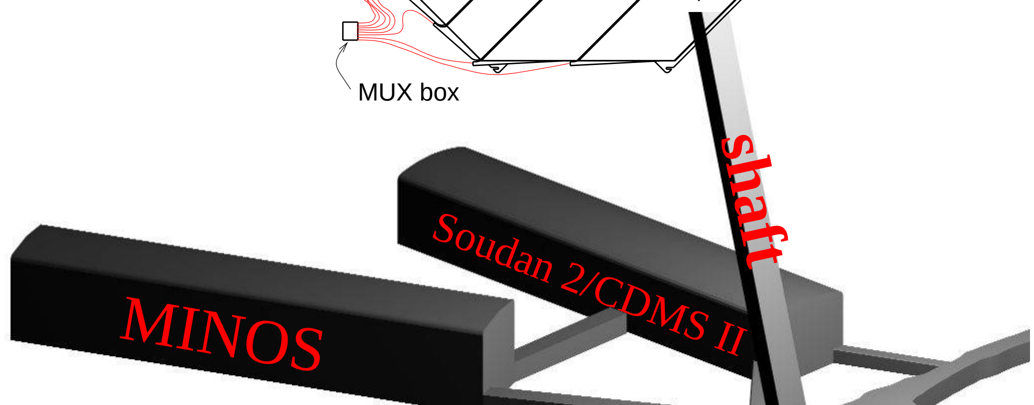
Far Detector – 735.3 km away

- **Located in Soudan mine**
- **5.4 kton**
- **Operation as similar as possible to near detector**
- **Two detectors used to reduce systematic effects**

- **B ~ 1.5T (R=2m)**
- **HAD ~ 55% / E $^{1/2}$**
- **EM ~ 23% / E $^{1/2}$**



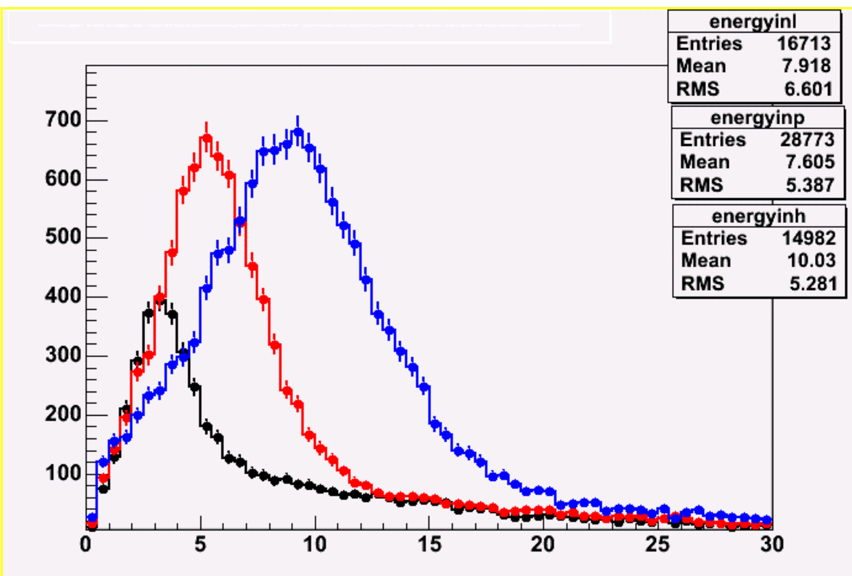




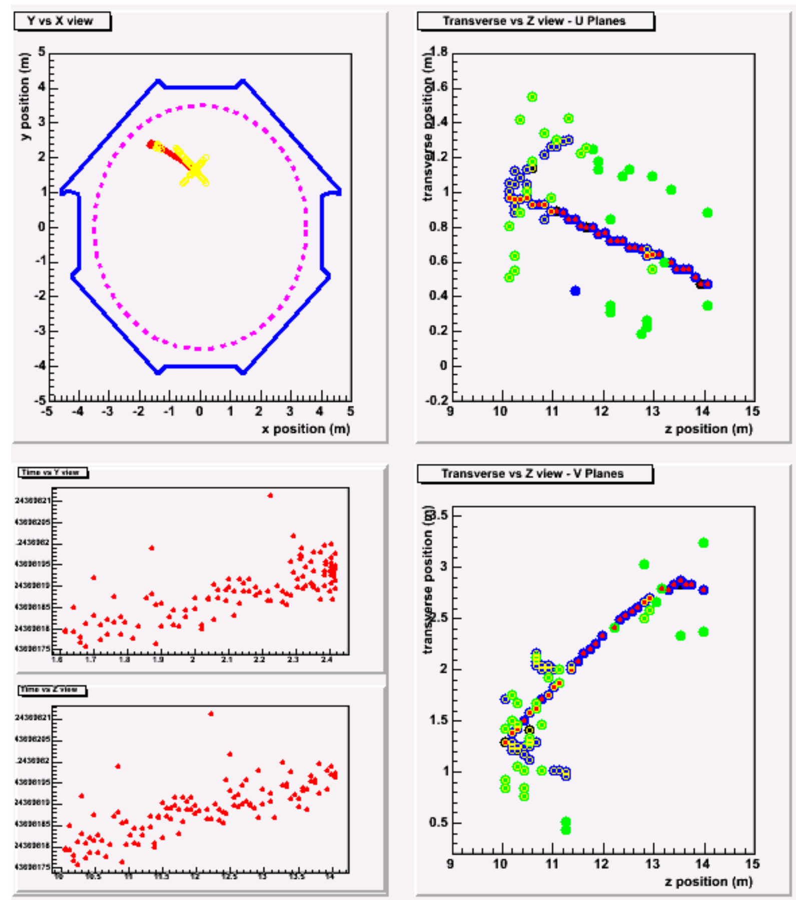
Minos Status

- Test Beam in December 2004
- Startup in March, 2005
- Collecting data steadily
- Detectors working well

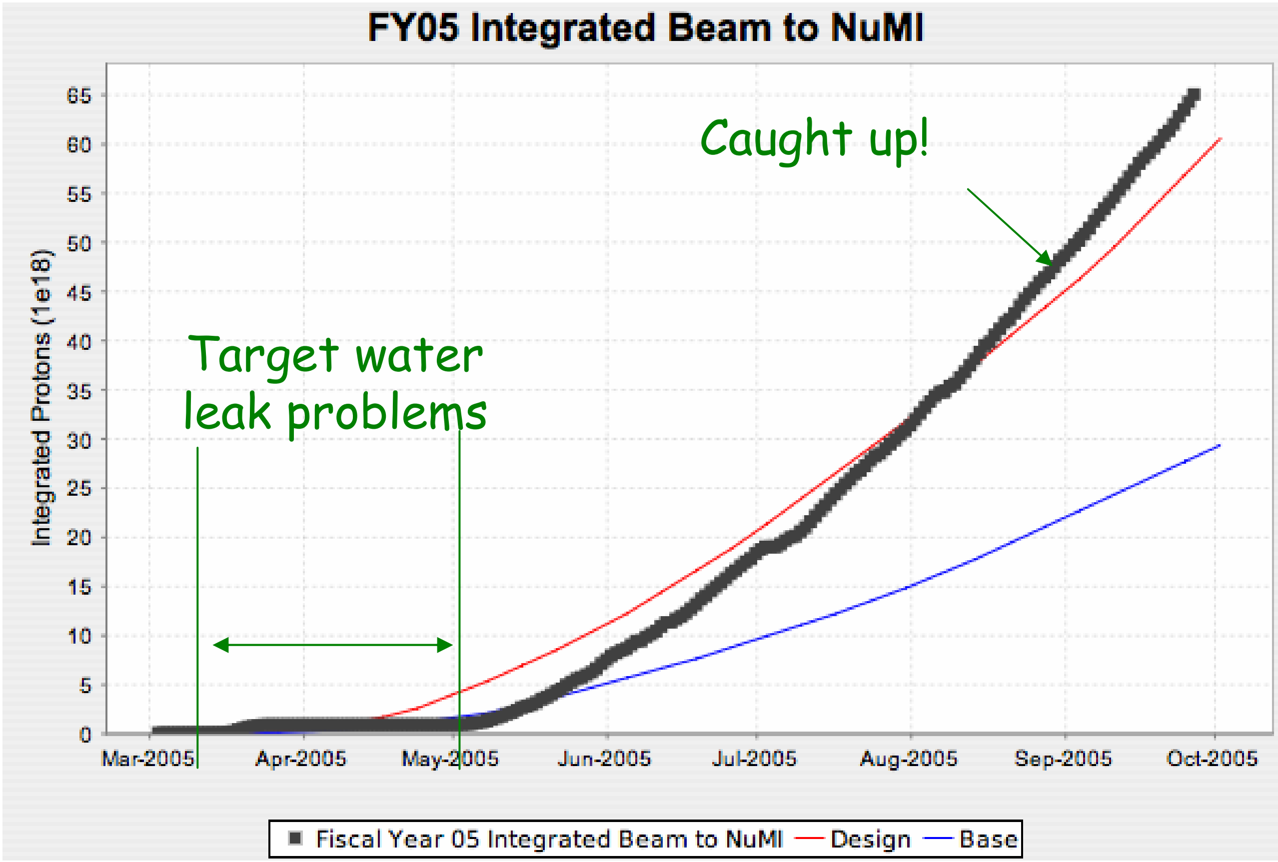
Near detector (different target positions)



Far detector (fully contained event)

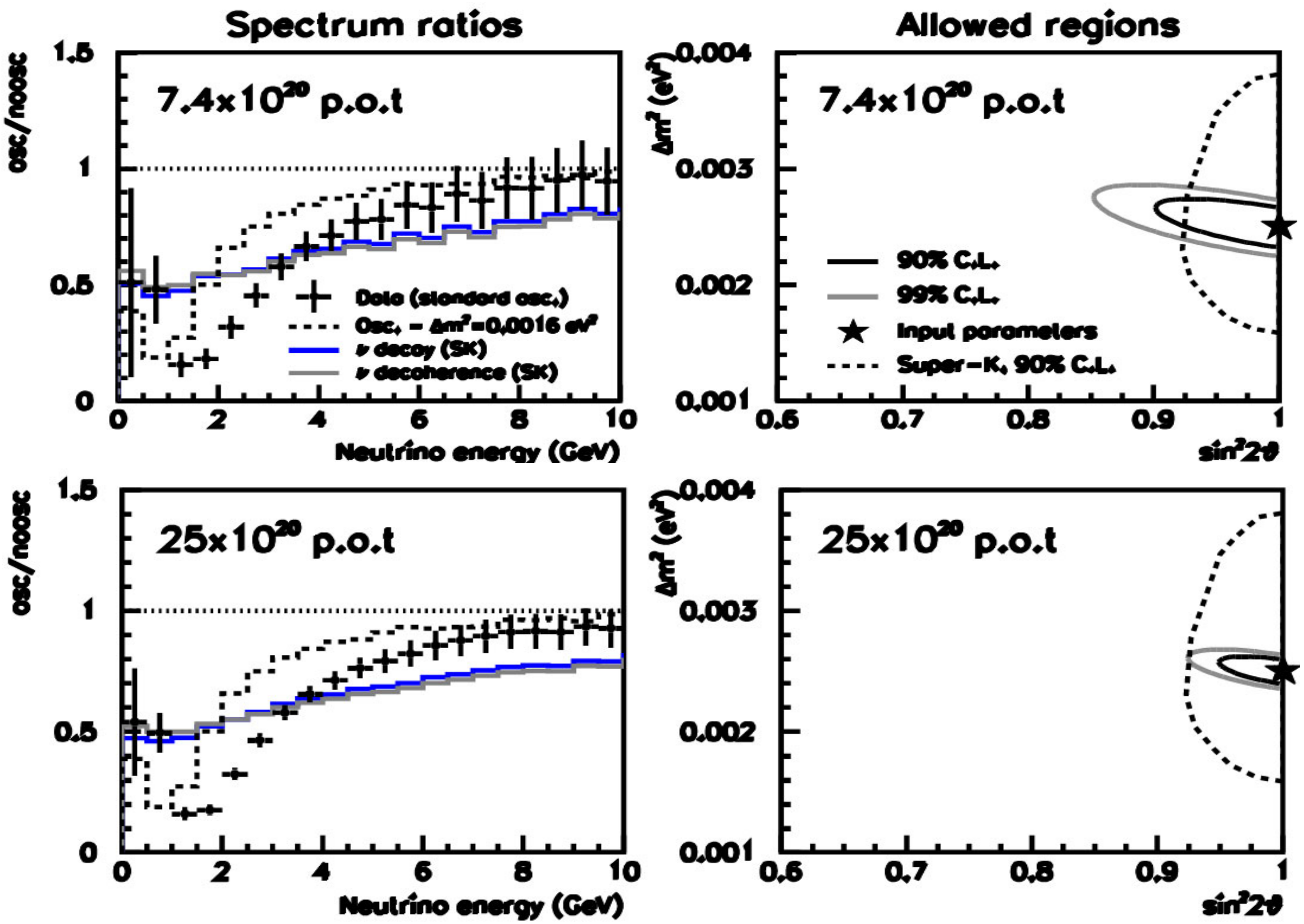


Beam to NuMI/MINOS



- Accumulating data at ~2-2.5E20/yr
- Can do initial oscillation (disappearance) result with 1E20 (~end of year, not counting analysis)

MINOS Ultimate Sensitivity

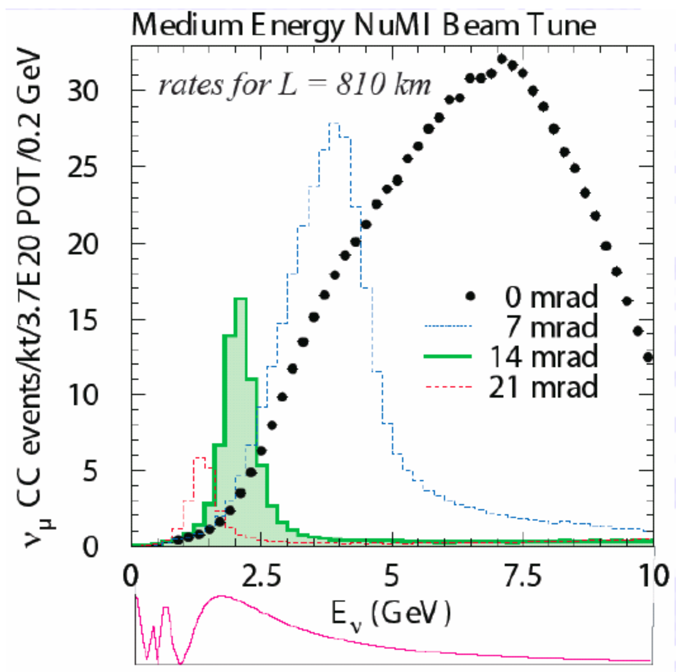


~3 years

~7 years

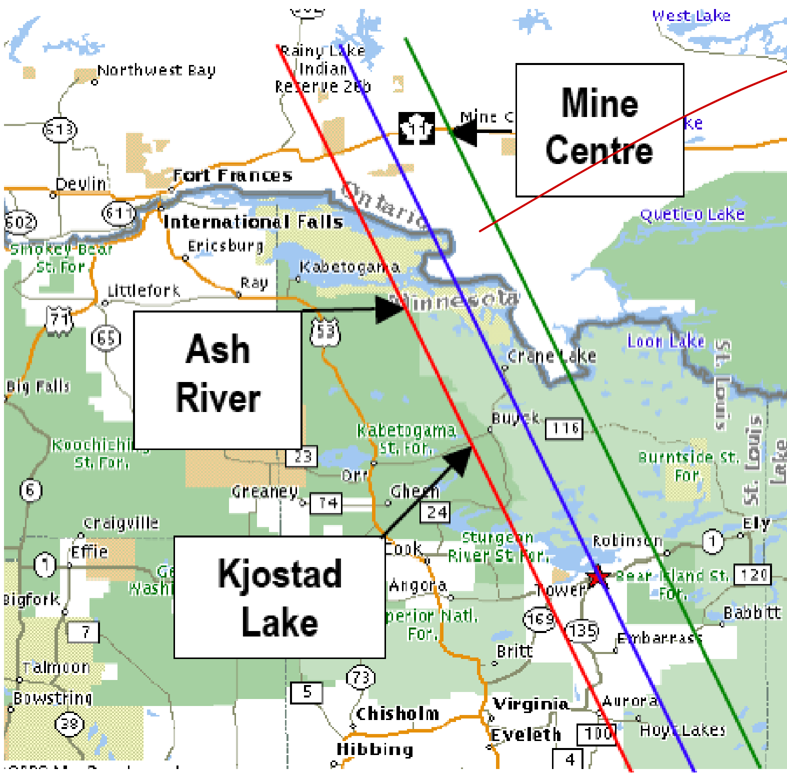
Beyond Minos – an Off-Axis experiment

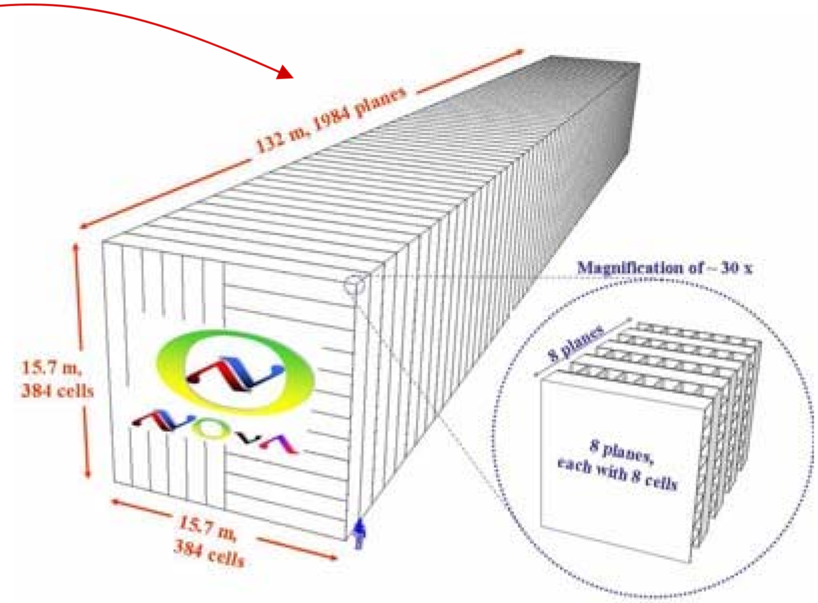
- Putting a Detector Off the NuMI Axis probes a narrower neutrino energy distribution than an on-axis experiment (albeit at a lower total intensity)
- By constraining L/E, one is able to resolve different contributions to the signal by comparing neutrino and anti-neutrino events
  - $\sin(\theta_{13})$
  - *Sign* of Δm^2 (resolve hierarchy question)
  - Next step to measuring CP violation



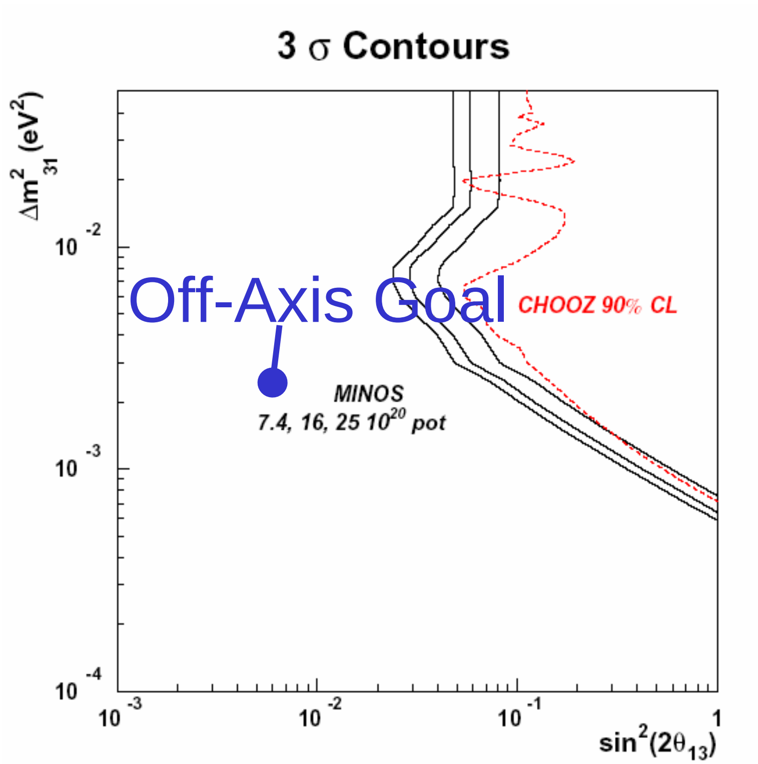
Nova Proposal

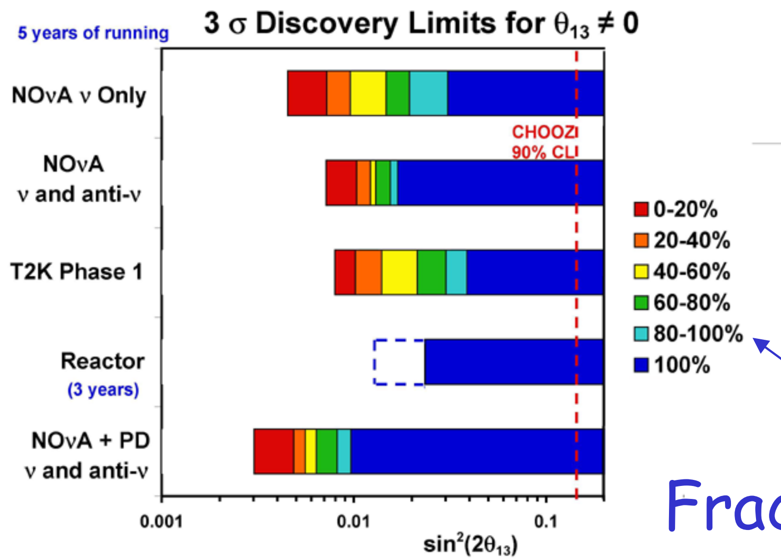
- Place a 30 kT fully active liquid scintillator detector about 14 mr off the NuMI beam axis



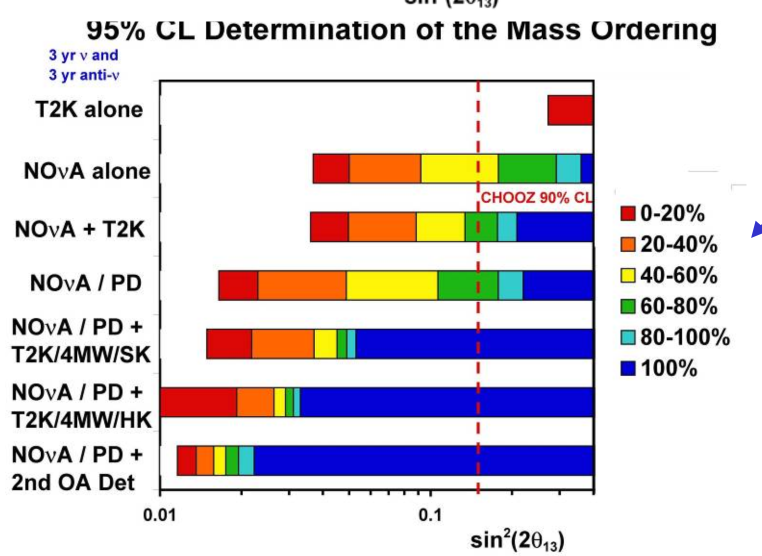


Nova Sensitivity





Fraction of δ covered



Nova Status and Schedule

- Stage I approval: April, 2005
- Project Start: October, 2006
- First kton operational: October, 2009
- All 30 ktons operations: July, 2011
- Problems:
  - Would really like a LOT of protons

So What's So Hard?

- Probability that a 120 GeV proton on the antiproton target will produce an accumulated pbar:

  .000015 (1.5E-5)

- Probability that a proton on the MiniBooNE target will result in a detected neutrino:

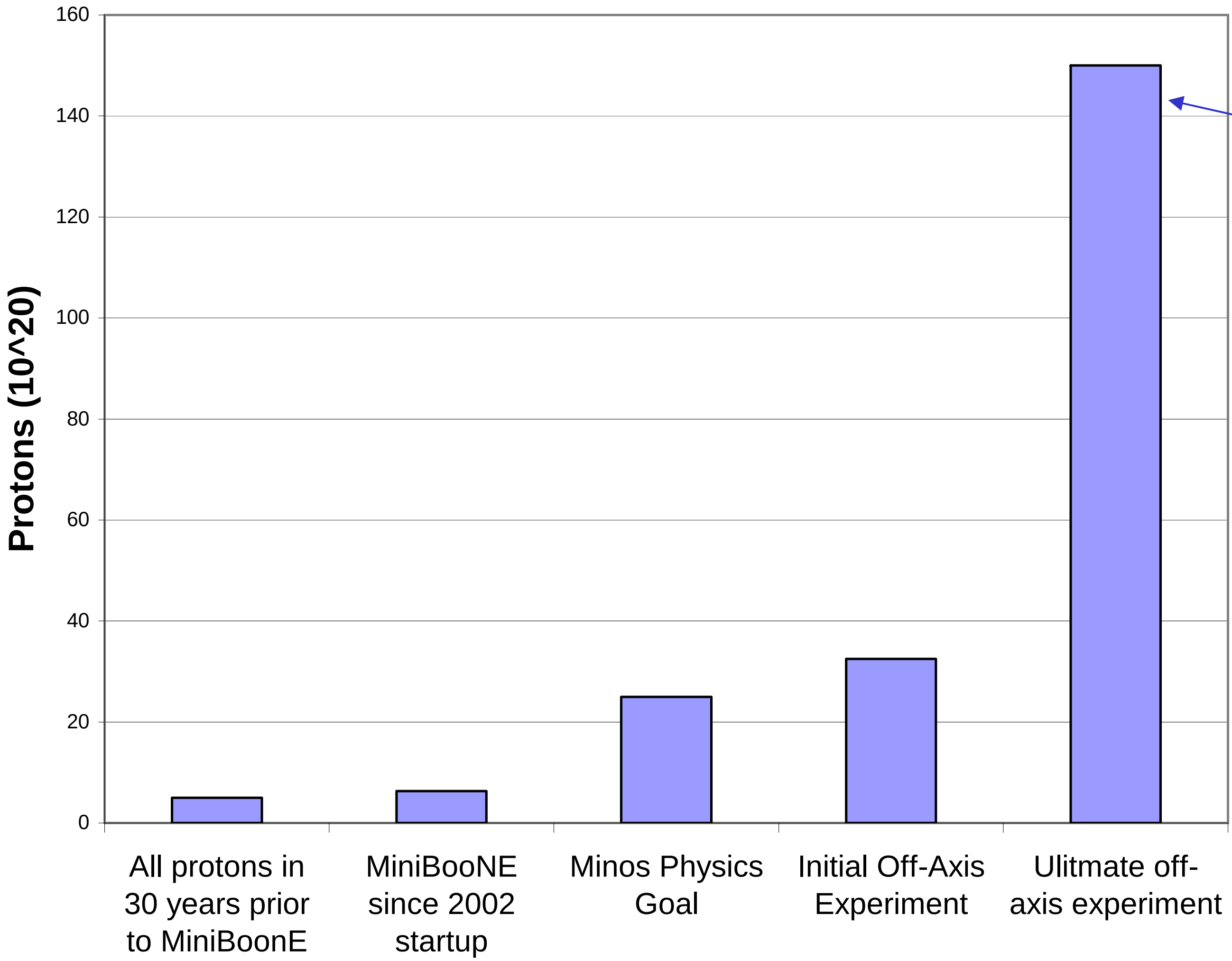
  .000000000000004 (4E-15)

- Probability that a proton on the NUMI target will result in a detected neutrino at the MINOS far detector:

  .000000000000000025 (2.5E-17)

⇒ Need more protons in a year than Fermilab has produced in its lifetime prior to these experiments!!

Proton Demands (in Perspective)



Highest number I could find on a plot

Limits to Proton Intensity

- Total proton rate from Proton Source (Linac+Booster):
  - Booster batch size
    - Typical ~5E12 protons/batch
  - Booster repetition rate
    - 15 Hz instantaneous, lower average
  - Beam loss
    - Damage and/or activation of Booster components
    - Above ground radiation

Operational Limit

- Total protons accelerated in Main Injector:
  - Maximum main injector load
    - ~5-6E13 presently
  - Cycle time:
    - 1.4s + loading time (1/15s per booster batch)

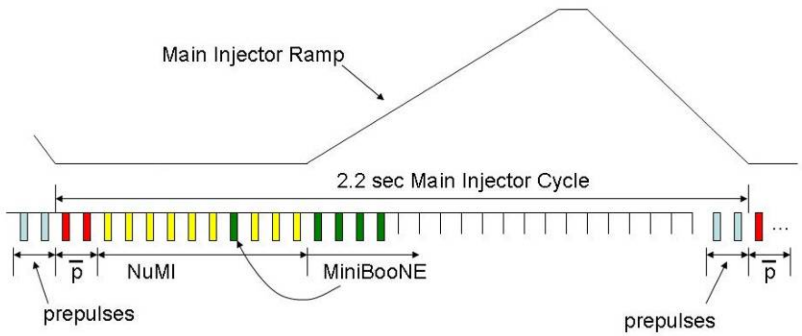
Staged Approach to Neutrino Program

"Proton Plan"

- Stage 0 (now):
  - Goal: deliver 2.5E13 protons per 2 second MI cycle to NuMI (~2E20 p/yr)
  - Deliver 1-2E20 protons per year to Booster Neutrino Beam (currently MiniBooNE)
- Stage 1 (~2007):
  - A combination of Main Injector RF improvements and operational loading initiatives will increase the NuMI intensity to ~5E13 protons per 2.2 second cycle (~3.5E20 p/yr)
  - It is hoped we can continue to operate BNB at the 2E20 p/yr level during this period.
- Stage 2 (post-collider):
  - Proton to NuMI will immediately increase by 20%
  - Consider (for example) using the Recycler as a preloader to the Main Injector and reducing the Main Injector cycle time (~6.5E20 p/yr)
  - The exact scope and potential of these improvements are under study
- Stage 3 (proton driver)
  - Main Injector must accommodate 1.5E14 protons every 1.5 seconds
  - NuMI beamline and target must also be compatible with these intensities.

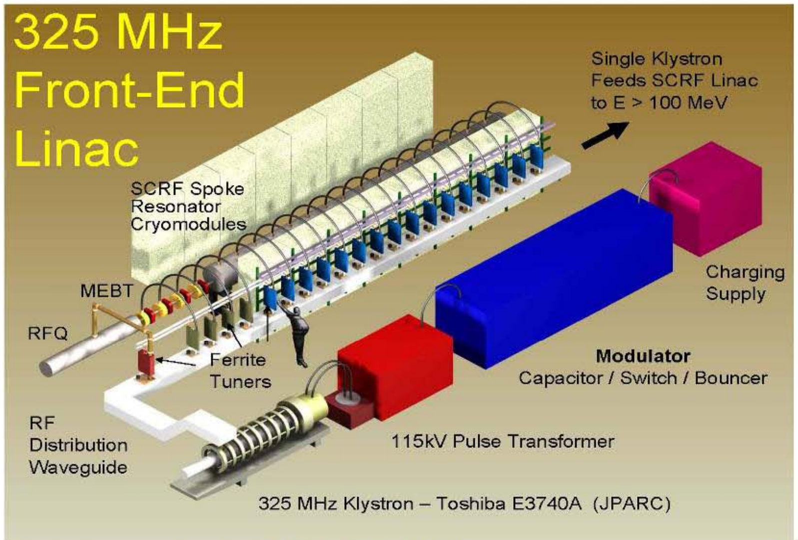
Re-tasking the Recycler

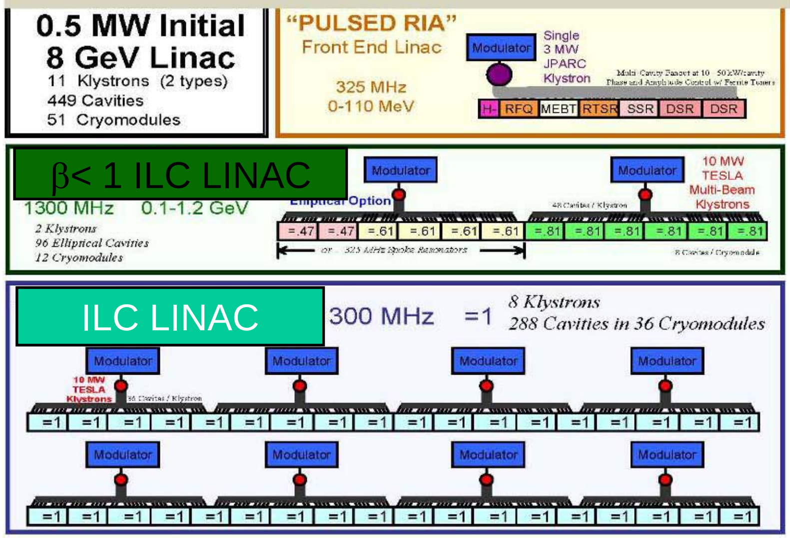
- At present, the Main Injector must remain at the injection energy while Booster “batches” are loaded.
  - Booster batches are loaded at 15 Hz
  - When we slip stack to load more batches, this will waste > 1/3 of the Main Injector duty factor.

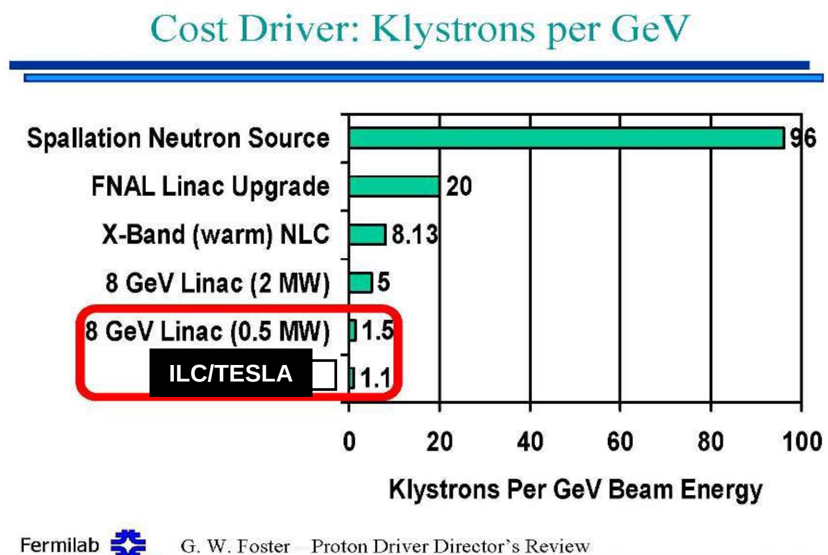


- After the collider, we have the option of “preloading” protons into the Recycler while the Main Injector is ramping, thereby eliminating dead time.
- Small invenstment
  - New beamline directly from Booster to Recycler
  - Some new RF
- Big payoff
  - At least 50% increase in protons to NuMI

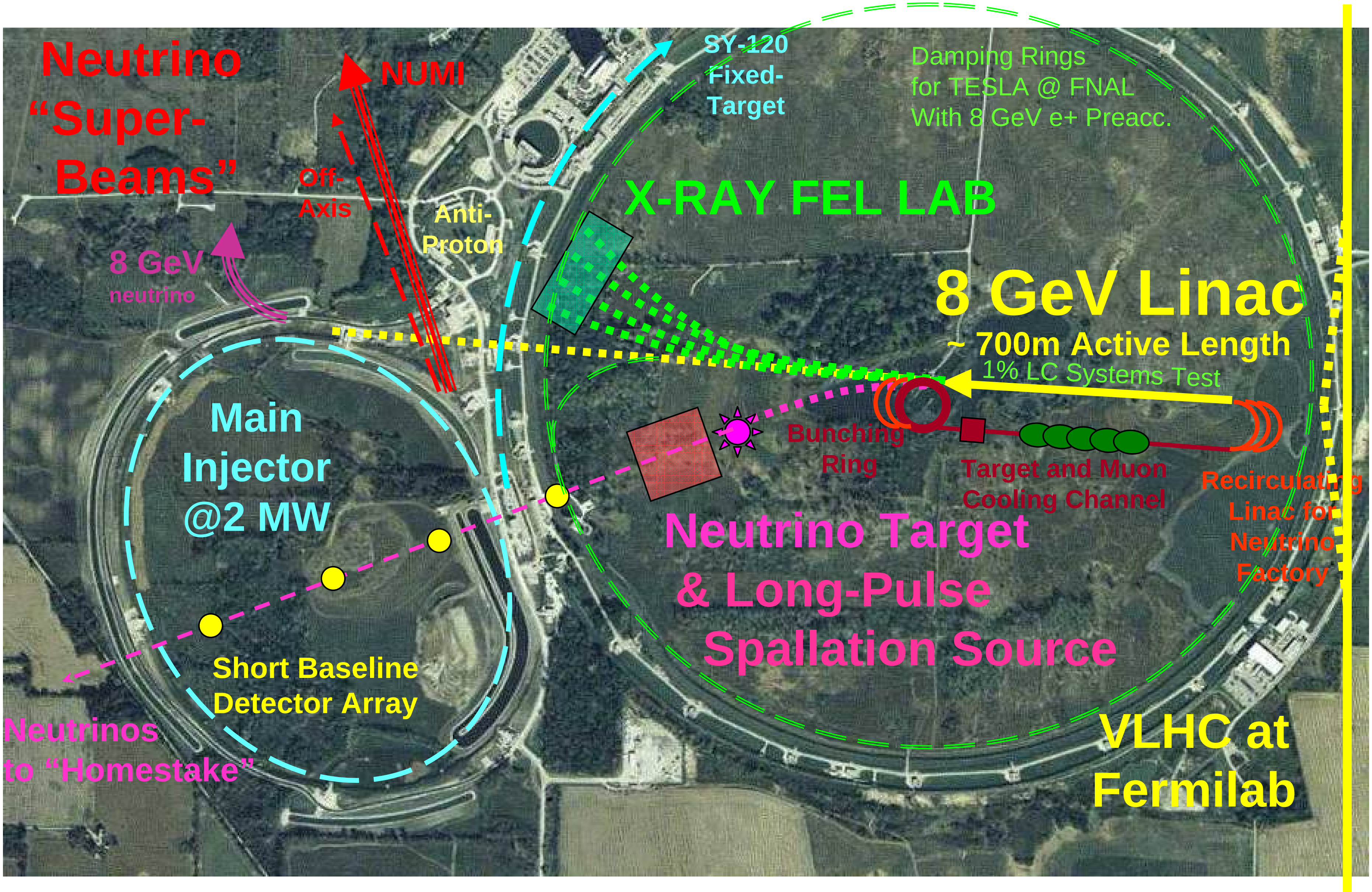
Thinking Big: A Proton Driver



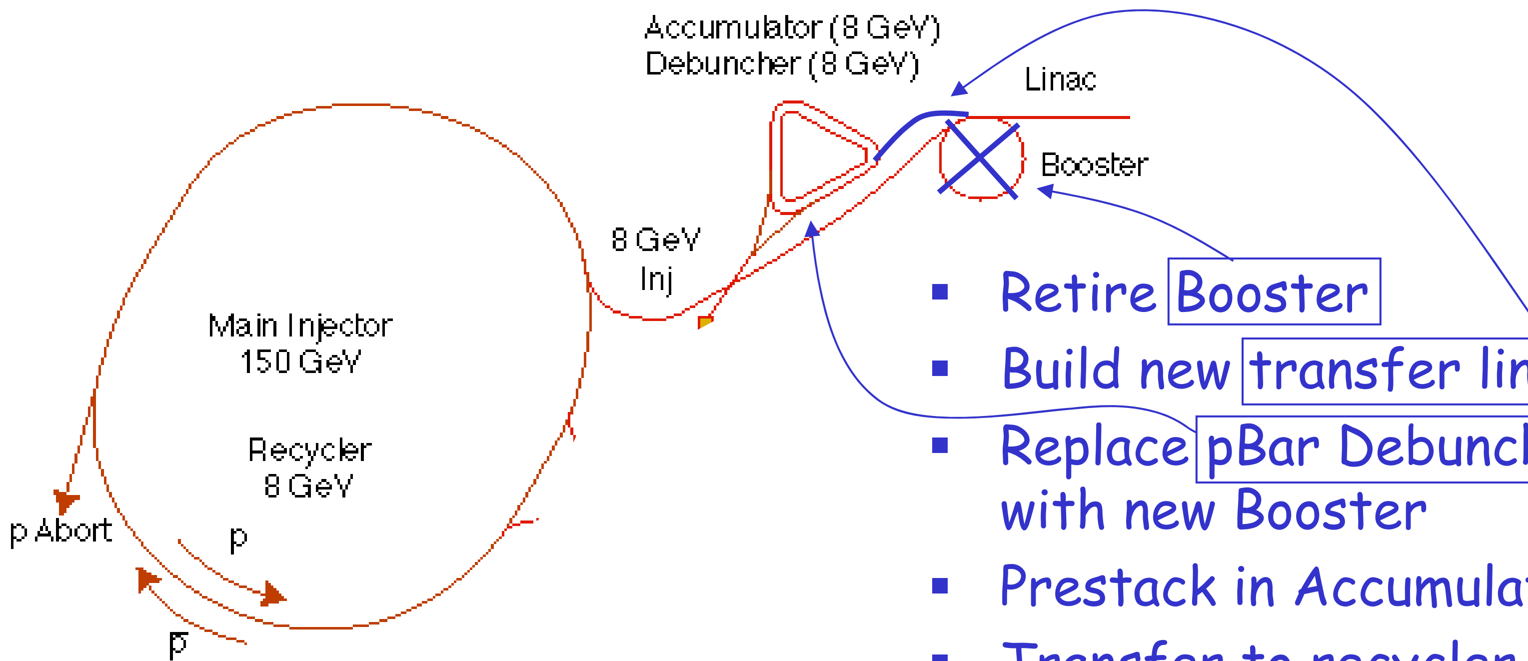




The Benefits of an 8 GeV Linac Proton Driver (stolen slide)



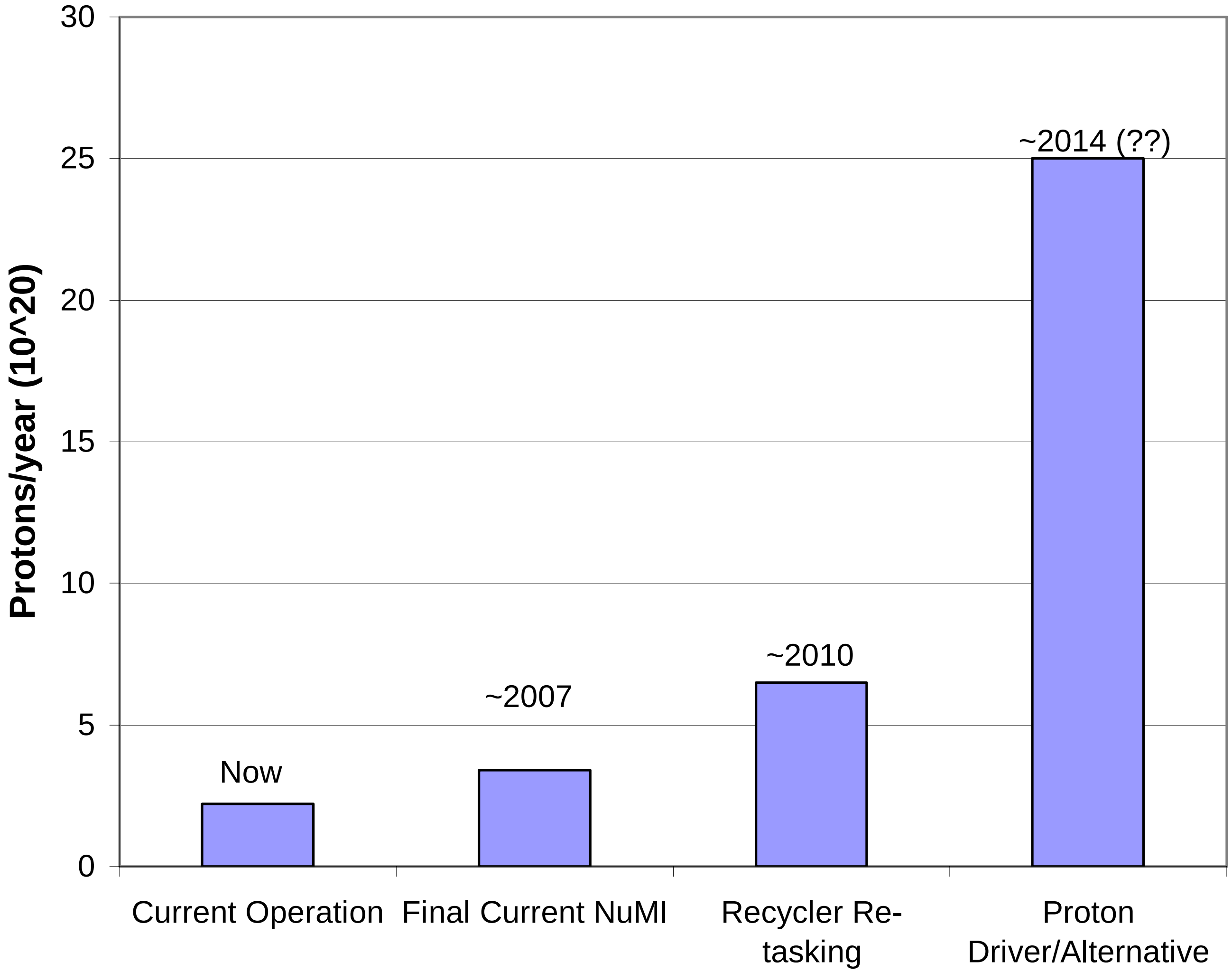
Possible "budget" Alternative to Proton Driver (D. McGinnis proposal)



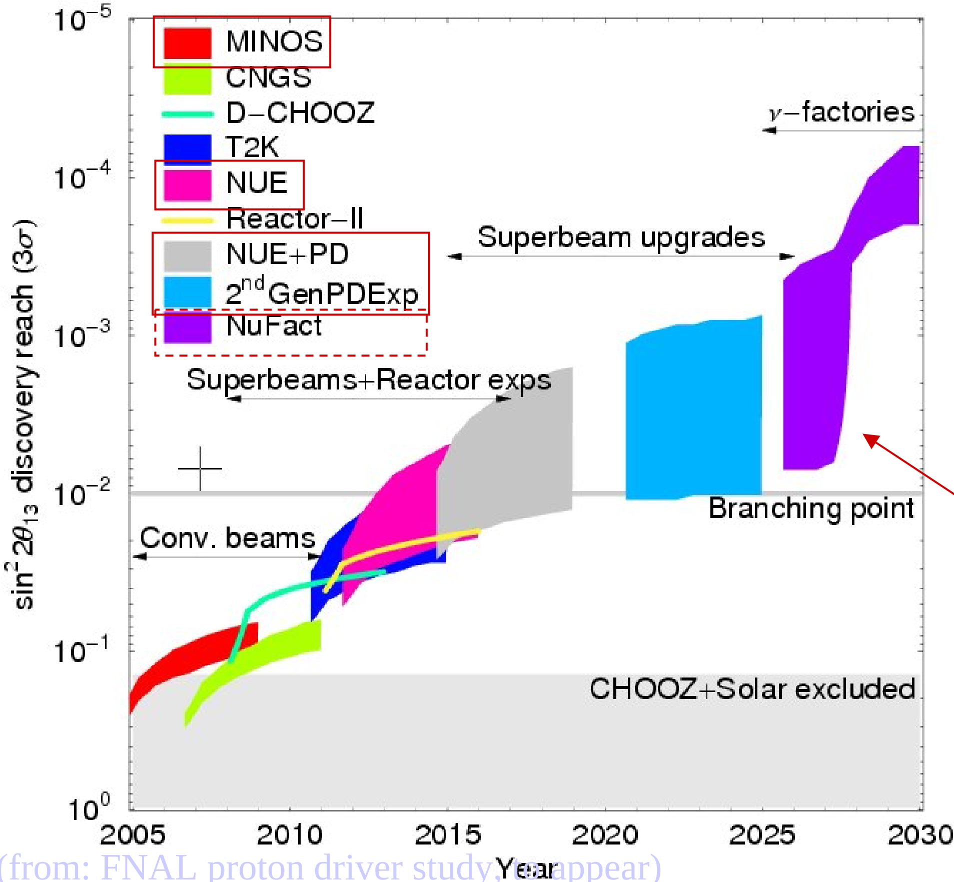
- Retire Booster
- Build new transfer line
- Replace pBar Debuncher with new Booster
- Prestack in Accumulator
- Transfer to recycler/Main Injector

- Less Expensive than the Linear Proton Driver
- Can get to 2 MW
- None of the side benefits
- No synergy with ILC

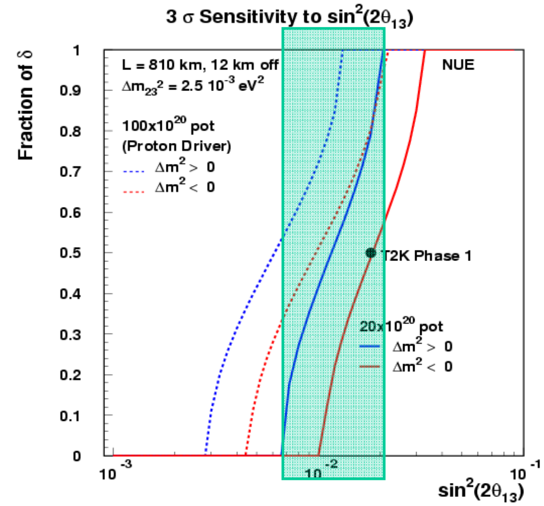
Evolution of Proton Delivery



Evolution of θ_{13} discovery limit



(from: FNAL proton driver study, to appear)

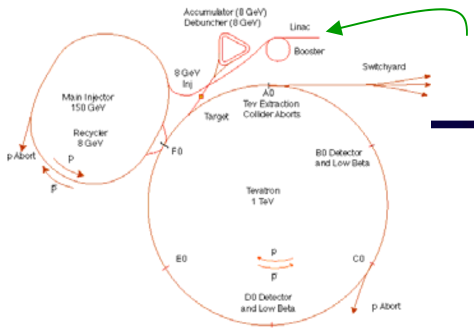


Bands show dependence on CP violation parameter δ

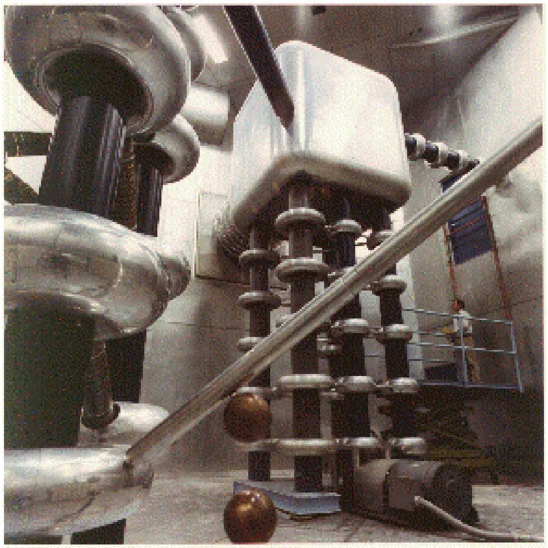
=located at Fermilab (NUE~Nova)

Conclusions

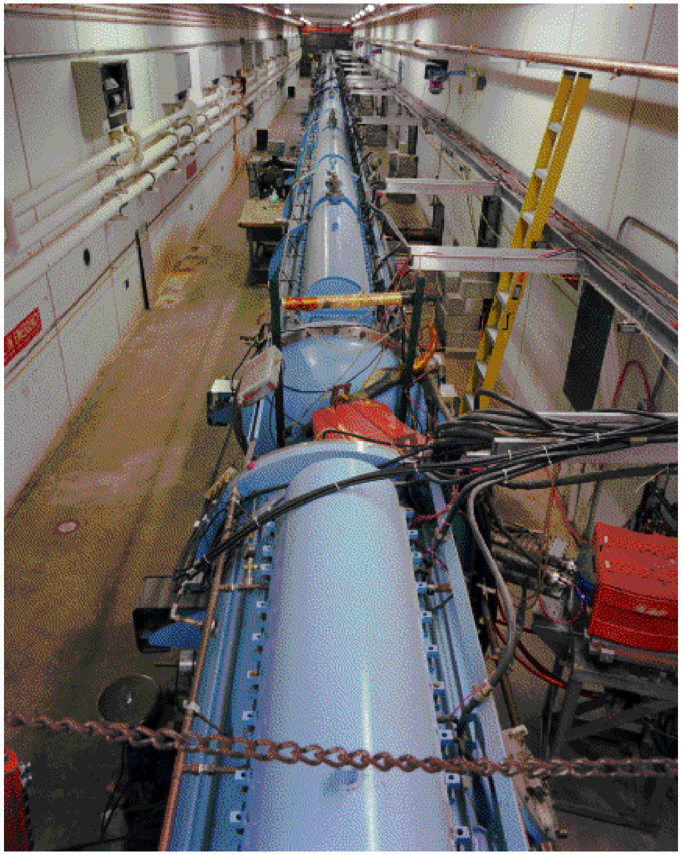
- It's a little disorienting to see the end of the Fermilab collider program
- We are disappointed at the cancellation of the BTeV project, nevertheless
- Fermilab is poised to hold a leading position in neutrino research for the next 10-15 years.



Preac(cellerator) and Linac

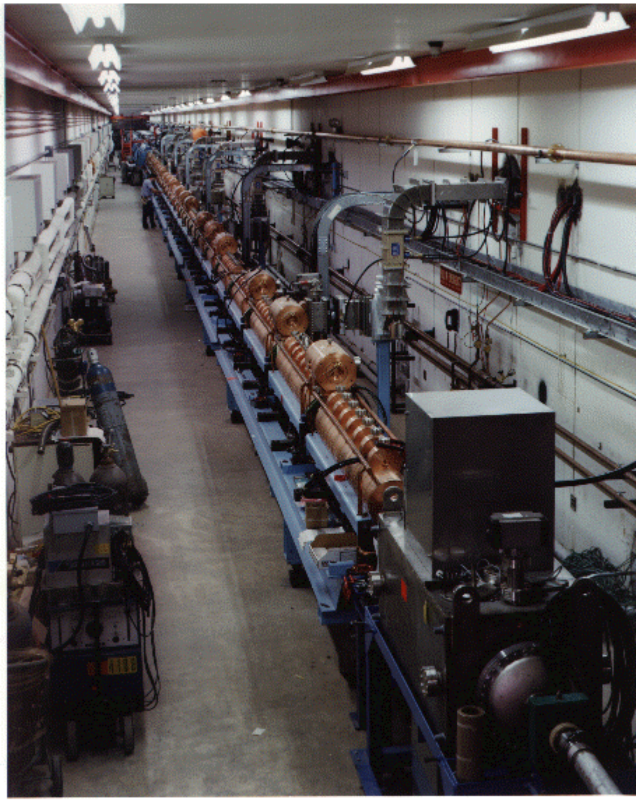


"Preac" - Static Cockroft-Walton generator accelerates H- ions from 0 to 750 KeV.



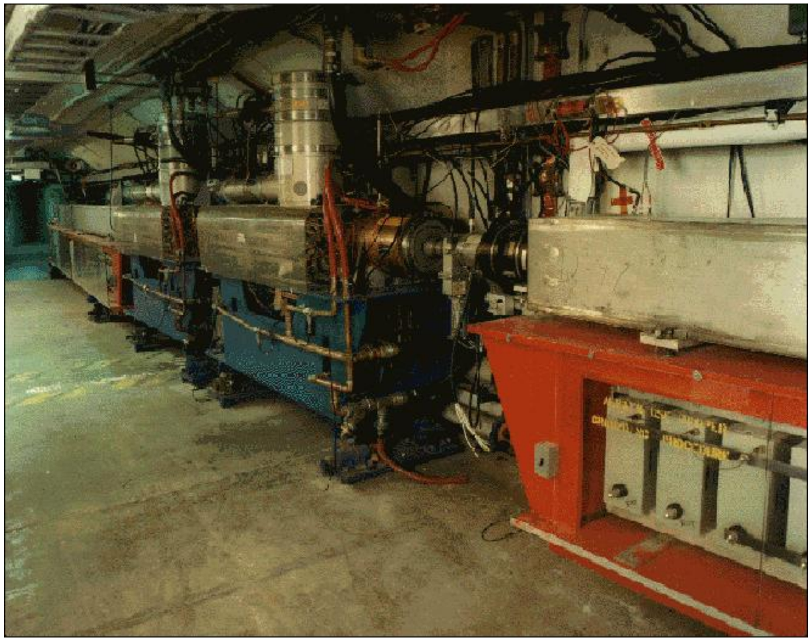
"Old linac"(LEL)- accelerate H- ions from 750 keV to 116 MeV

"New linac" (HEL)- Accelerate H- ions from 116 MeV to 400 MeV

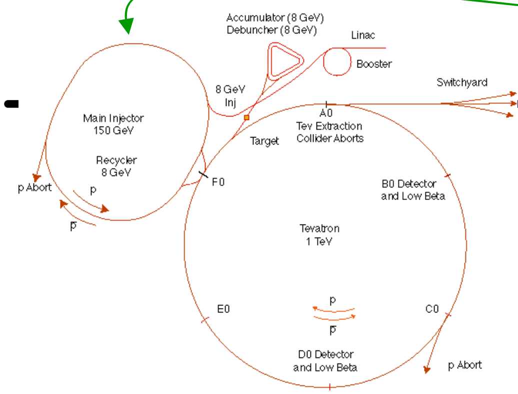


Booster

- Accelerates the 400 MeV beam from the Linac to 8 GeV
- From the Booster, beam can be directed to
  - The Main Injector
  - MiniBooNE (switch occurs in the MI-8 transfer line).
  - The Radiation Damage Facility (RDF) – actually, this is the old main ring transfer line.
  - A dump.
- More or less original equipment



Main Injector



- The Main Injector can accept 8 GeV protons OR antiprotons from
  - Booster
  - The anti-proton accumulator
  - The Recycler (which shares the same tunnel)
- It can accelerate protons to 120 GeV (in a minimum of 1.4 s) and deliver them to
  - The antiproton production target.
  - The fixed target area.
  - The NUMI beamline.
- It can accelerate protons OR antiprotons to 150 GeV and inject them into the Tevatron.